Development of a Surplus Production Model Applicable to British Columbia Offshore Stocks of Lingcod (*Ophiodon elongates*)

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Lingcod (*Ophiodon elongatus*) (family Hexagrammidae) is found on the west coast of North America, and in particular off the coast of British Columbia. This species has been exploited offshore in four distinct areas since the development of the bottom trawl fishery in the 1940s. The last yield recommendations for B.C. offshore stocks were provided by King and Surry in 2000. The Total Allowable Catch limits have remained the same in the four areas since 1998 following the recommended yield options supplied by Leaman and McFarlane in 1997. Here, a Bayesian analysis of biological data was used to estimate the growth, length to weight conversion and maturity parameters for both sexes in the four areas. A state-space Schaefer production model was fitted to annual catch biomass from commercial and recreational fisheries and to several abundance index time series from commercial and scientific survey data. This is the first time that the stocks have been assessed using a Bayesian framework. An informative prior was formulated for the intrinsic rate of increase using a demographic methodology and assuming a Ricker recruitment hypothesis for lingcod, which is known to be a cannibal species. The results of the assessment are only presented for the most exploited stock - the southwest coast of Vancouver Island stock. The abundance of this stock has been increasing since the late 90s and is very close to the B_{MSY} in 2009 (about 50% of un-fished stock size). The implementation of a TAC of 950 t since 1998 allowed for the rebuilding of the stock. According to the stock projections presented here, the TAC should stay below 1100 t in the future years to allow a sustainable fishery.

RÉSUMÉ

Cuif, M., McAllister, M., and King, J.R. 2009. Development of a surplus production model applicable to British Columbia offshore stocks of lingcod (*Ophiodon elongates*). Can. Tech. Rep. Fish. Aquat. Sci.: 2861: xii + 72 p.

La morue-lingue (*Ophiodon elongatus*) est un Hexagrammidae que l'on trouve sur la côte ouest de l'Amérique du Nord. Cette espèce est exploitée en particulier au large des côtes de la Colombie Britannique (C.B.) dans quatre zones distinctes depuis le développement de la pêche au chalut de fond dans les années 1940. Les dernières recommandations de gestion des stocks de morue-lingue au large de la C.B. ont été fournies par King et Surry en 2000. Les TACs (Captures Totales Admissibles) sont restées les mêmes dans les quatre zones depuis les recommandations de Leaman et McFarlane en 1997. Une analyse statistique Bayésienne de données biologiques a permis d'estimer les paramètres de croissance, de conversion taille-poids et de maturité pour les deux sexes dans les quatre zones de répartition de la morue-lingue. Un state-space modèle de production de Schaefer a été ajusté à une série de captures totales provenant des pêcheries professionnelles et récréatives et à plusieurs séries d'indices d'abondances provenant de campagnes scientifiques et commerciales. Les quatre stocks de morue-lingue sont évalués dans un cadre Bayésien pour la première fois. Un prior informatif a été formulé pour le taux de croissance intrinsèque grâce à une méthode démographique en supposant un recrutement de forme Ricker connaissant le comportement cannibale de la morue-lingue. Les résultats de l'évaluation de stock sont présentés pour le stock le plus exploité situé au sud ouest de l'île de Vancouver. L'abondance de ce stock augmente depuis les années 1990 et est très proche de B_{MSY} en 2009 a savoir 50% de la taille du stock non exploité. La mise en place d'un TAC de 950 t en 1998 a permis un rétablissement du stock. Le TAC devrait rester inferieur a 1100 t dans les années futures pour permettre une exploitation durable du stock.

INTRODUCTION

The last assessment of the B.C. offshore stocks of lingcod (*Ophiodon elongatus*) was undertaken by Leaman and MacFarlane (1997). They provided management advice for the four offshore lingcod stocks: Statistical Area 3C, 3D, 5AB and 5CDE. For area 3C, they provided yield options based on the results of a catch-at-age model fitted to trawl fishery catch-at-age data and a commercial catch per unit effort (CPUE). For the three other stocks, the recommended management measures were based on informal analyses of total annual catch and effort data. This assessment suggested declines in the abundance of these stocks in the 1990s. The authors recommended implementing a conservative management regime in area 3C. Recommended yields were less than 1000 t, 400 t (low risk) to 800 t (high risk), and 1100 t (low risk) to 2200 t (high risk) for area 3C, 3D, and 5AB, respectively. With a lack of biological data for area 5CDE, the recommended yield was set at 1000 t out of concern for the rapid expansion of the fishery in the area in the 1990s. King and Surry (2000) updated the data and revised the management advice without updating the assessment model. The present commercial TACs have remained the same since 1998, i.e., 950 t in area 3C, 400 t in area 3D, 1062 t in area 5AB and 1000 t in area 5CDE.

We use updated commercial and research data to develop surplus production models applicable to the four outside stocks of lingcod. We adopted a Bayesian statistical approach to fit the model to the data, a novel approach in B.C. offshore lingcod assessments. A Bayesian framework can improve management advice by reducing uncertainty in stock sizes estimates (McAllister *et al.*, 1994) through the use of informed priors, which incorporate previous knowledge and expert judgment (McAllister and Kirkwood, 1998). This statistical framework allowed us to include a risk analysis and an investigation of appropriate management reference points as recommended in Leaman and McFarlane (1997) for the future lingcod stock assessments.

METHODS

BAYESIAN FRAMEWORK

The Bayesian statistics require the use of a likelihood function $L(\text{data}|\theta_i)$, the probability of obtaining data under the assumption that they are generated by a model containing parameters θ_i (Clark, 2005), as in frequentist statistics. The key aspect of Bayesian analysis is the use of prior probabilities $p(\theta_i)$. Prior probabilities allow for introducing information from expert judgment and from former data, prior to obtaining the actual set of data, and for characterizing uncertainty in the unknowns with the use of probability distributions for them. The prior distribution is updated by the data in Bayes theorem in order to compute the posterior probability, probability that a given state of nature *i* is true conditioned on the data $P(\theta_i|\text{data})$. A state of nature is one potential realisation of the set of all possible values for θ_i.

$$P(\theta_i \mid \text{data}) = \frac{L(\text{data} \mid \theta_i) p(\theta_i)}{\int L(\text{data} \mid \theta) p(\theta) d\theta}$$

When data include little information the posterior probability density function (pdf) tends to reflect the prior pdf. Nevertheless, as data become more informative, $L(\text{data}|\theta_i)$ prevails and priors lose their influence over the posterior (McAllister *et al.*, 1994).

ALGORITHMS USED TO PRODUCE THE POSTERIOR DISTRIBUTIONS

Sampling Importance Resampling (SIR) for biological parameter estimations

Principle: Samples of model input parameter values, ($\theta_1, \theta_2, \ldots, \theta_k$) are randomly drawn from an importance function $g(\theta)$, i.e. a joint pdf of θ. The procedure requires that for each vector θ_i that is drawn from $g(\theta)$, an importance weight is calculated:

$$w(\theta_i) = \frac{L(\text{data} \mid \theta_i) p(\theta_i)}{g(\theta_i)}$$

The posterior pdf of θ is estimated by normalizing the importance weights:

$$F(\theta_i \mid \text{data}) = \frac{w(\theta_i)}{\sum_{i=1}^{k} w(\theta_i)}$$

The distribution $F(\theta|\text{data})$ over ($\theta_1, \theta_2, \ldots, \theta_k$) approximates the actual posterior distribution $P(\theta|\text{data})$. This approximation improves as k increases (McAllister *et al.*, 1994).

Finally a large number of θ_i is drawn randomly with replacement from ($\theta_1, \theta_2, \ldots, \theta_k$) with probabilities proportional to $w(\theta_1), w(\theta_2), \ldots, w(\theta_n)$. The resulting sample approximates an independent and identically distributed (i.i.d.) sample from the joint posterior pdf of θ.

Importance function: The importance function must be constructed to be as similar as possible to the actual posterior density function of interest but with tails less sharp than those of the actual posterior pdf (McAllister *et al.*, 2001). The aim is to avoid a large proportion of small weights, $w(\theta_i)$, so that the risk of large variance or failure in convergence of estimated posterior is reduced as advised in Oh and Berger (1992). The chosen importance function is often the prior (Kinas, 1996).

The Multivariate Student (MVT) distribution has often been used as an importance function (McAllister and Ianelli, 1997). An advantage of this function over the multivariate normal is that the tails of the distribution can be adjusted so that the density in its tails is slightly greater than the density in the tails of the posterior distribution (McAllister and Ianelli, 1997).

Efficiency of the sampling: The ratio of the maximum importance weight to the sum of all $w(\theta_i)$ all over the draws is a basic index of sampling efficiency. If the sample was

taken from the posterior, this proportion would equal to $1/k$, where k is the number of draws from the importance function, given that each $w(\theta_i)$ would be equal to some constant (McAllister and Ianelli, 1997).

Metropolis-Hastings within Gibbs sampling for the production model parameters estimation

In order to produce the posteriors of the production model parameters, we used Metropolis-Hastings within Gibbs sampling.

According to Smith (1991) it is likely that SIR is more efficient than the Markov chain approach for drawing a sample from the posterior. On the other hand Gibbs sampler is very easy to implement, requiring very little numerical or stochastic simulation expertise. Besides, in very complex problems it can be too difficult to identify any appropriate importance sampling strategy (Smith, 1991).

ANALYSES OF THE BIOLOGICAL DATA FOR THE OUTSIDE LINGCOD POPULATION

Biological data were supplied by DFO. The biological samples extend from 1977 to 2008 and were taken from commercially caught lingcod by on board scientific observers and from research surveys. The key data used in the following analysis are the length-at-age, the weight-at-age and the number of mature at age for each sex. Lingcod samples were aged using a fin ray methodology developed in 1977 (Cass *et al.*, 1990). Some problems occurred in the late 1980s and early 1990s in ageing of lingcod samples but these samples were re-aged (Leaman and McFarlane, 1997).

Estimation of the growth parameters

The growth of fish that are old enough to be exploited can often be accurately described by the von Bertalanffy equation. The three von Bertalanffy growth parameters (L_∞, K and t_o) were estimated for lingcod using a Bayesian estimation model for each area with length at age data for each sex. L_∞ is the mean asymptotic length of old fish, K is the growth rate coefficient and t_o is the theoretical age of length zero. Relatively uninformative priors on K, L_∞ and t_o were used and were similar for each area. The prior probability distribution function (pdf) of K was normal with a mean of 0.5 year^{-1} and a standard deviation of 10 year^{-1}. The prior pdf of L_∞ was normal with a mean of 2000 mm and a standard deviation of 2000 mm. The prior pdf of t_o was normal with a mean of 0 year and a standard deviation of 500 years. It was assumed that sigma (σ_g), the standard deviation in the error deviation between the length observed and the length predicted, was uniformly distributed over log of sigma over the interval [log(0.000001), log(100)]. A normal probability density function was used to represent the probability of the observation given the model prediction of the length at age L_t:

$$L_t \sim \text{Norma}\left(L_\infty\left(1-e^{-K(t-t_0)}\right), \sigma_g^2\right)$$

The sampling importance resampling (SIR) algorithm was applied in order to obtain the posterior probability distributions. The steps followed for computation of the importance function were those developed in McAllister and Ianelli (1997). The posterior mode of each parameter was first obtained from a nonlinear minimization procedure based on a gradient search method that uses numerical derivatives. Then the Hessian matrix was estimated using numerical derivatives of the log of the posterior kernel (i.e., the likelihood times the prior) at its mode. The actual joint posterior distribution was approximated by a multivariate student distribution with 25 degrees of freedom which has worked well in several other fisheries applications (e.g., McAllister and Ianelli 1997; McAllister et al. 2001). This distribution was used as an importance function for the SIR, with a mean equal to the posterior mode and a variance estimated by the negative inverse of the Hessian matrix. For all model runs, the maximum weight (or maximum importance ratio) for a single draw as a percentage of the total cumulative posterior weight dropped below 0.40% within one million draws from the importance function. The sampling was consequently considered efficient.

Estimation of the maturity parameters

The fraction mature at age was modelled using a normalized and discretized cumulative lognormal density function which appeared to fit the fraction mature at age better than a logistic function. The cumulative lognormal density function included two maturity parameters: the median age mature (*med_age*) and sigma (σ_{mat}), the standard deviation in the log fraction maturing at age. The parameters of the function of fraction mature at age were estimated using a Bayesian approach for each area, using maturity data for each sex. The prior pdf of the median age mature was assumed to be uniform over the interval [1 year, 20 years]. The prior pdf on the sigma age mature was presumed to be uniform over the log of sigma over the interval [log(0.000001), log(100)].

The cumulative distribution was formed from the following steps:

(1) Computation of the log normal density at age (*ldens$_t$*) from age 1 to maximum age,

$$ldens_t = \frac{1}{t\sigma_{mat}\sqrt{2\pi}}\exp\left(\frac{-(\log(t)-\log(med\_age))^2}{2\sigma_{mat}^2}\right)$$

(2) Computation of the total density (*totdens*) by summing all densities over all ages,

$$totdens = \sum_{t=1}^{\max t} ldens_t$$

(3) Calculation of the probability for each age (*prob$_t$*) by normalizing the density at age,

$$prob_t = \frac{ldens_t}{totdens}$$

(4) Calculation of the cumulative probability from age 1 to the maximum age:

$$fmat_t = \sum_{a=1}^{t} prob_a$$

A binomial distribution was used to represent the likelihood of each observed number mature at age (nb_mat_t).

$$nb\_mat_t \sim \text{Binomial}(fmat_t, nb\_tot_t)$$

Where nb_tot_t is the total number of fish observed at age t and $fmat_t$ is the fraction mature at age t.

The posterior mode of each parameter was estimated by nonlinear minimization and the variance and covariance at the mode were estimated by the negative inverse of the Hessian matrix. The posterior mean was approximated by the posterior mode based on the central limit theorem which is reasonable given the large sample sizes (100s of fish). The posterior variance and covariance were approximated by the posterior variance and covariance at the mode.

Estimation of the length to weight conversion parameters

The length to weight conversion parameters (a, b) were estimated using a Bayesian estimation model for each area. a is the intercept or proportionality constant and b is the length exponent. Length-at-age and weight-at-age data for each sex were used. The data collected during the reproduction period were excluded from this analyse because of the changes in the shape of the fish during the spawning season months from October to March. The prior pdf of a was normal over log of a with a mean of 0 and a standard deviation of 100. The prior pdf of b was normal with a mean of 0 and a standard deviation of 100. The prior pdf of sigma (σ_{ab}), the standard deviation in the error deviation between the log weight observed and the log weight predicted, was uniform over the log of sigma over the interval [log(0.000001), log(10)].

A normal probability density function was presumed to represent the probability of the observation given the model prediction of the log weight at age $\log(W_t)$:

$$\log(W_t) \sim \text{Normal}\left(\log(a) + b\log(L_t), \sigma_{ab}^2\right)$$

The posterior mode of each parameter was estimated by nonlinear minimization and the variance and covariance at the mode were estimated by the negative inverse of the Hessian matrix. The posterior mean was approximated by the posterior mode regarding the central limit theorem. The posterior variance and covariance were approximated by the posterior variance and covariance at the mode.

SURPLUS PRODUCTION MODEL USED FOR THE STOCK ASSESSMENTS

In order to conduct the four lingcod stocks assessments, we chose to apply a relatively simple stock assessment model, commonly used, which is the surplus production model (SPM) or biomass dynamic model (Hilborn and Walters, 1992). SPMs do not require animals to be aged. This type of model takes into account the production resulting from recruitment and growth, as well as natural morality and catch. This model does not take into account emigration or immigration of fish, and is thus suitable for a non-migratory species like lingcod. The surplus production is the net change in stock biomass which would occur if there was no fishing, i.e., the catch that could be taken to keep stock biomass constant (Hilborn and Walters, 1992).

The estimation performance of a simple production model has been found in some instances to be as good or better than age-structured models even when age-structured data were available (Ludwig and Walters, 1985; Polacheck at al., 1993).

The surplus production model used is the Schaefer production model (1954), which is widely applied in fisheries stock assessment (Meyer and Millar, 1999). This model is indeed mathematically simple and has relatively few parameters to estimate (McAllister *et al.,* 1999). Moreover this model can address our management and decision objectives. Schaefer's model is normally written:

$$\frac{dB_y}{dt} = rB_y\left(1 - \frac{B_y}{\mathrm{K}}\right) - C_y$$

where y is the year, B_y the stock biomass at the start of year y, r the intrinsic rate of increase, K the carrying capacity and C_y the catch during year y which is assumed is proportional to the stock size.

Schaefer biomass dynamic model is defined by the following equation:

$$B_{y+1} = B_y + rB_y\left(1 - \frac{B_y}{\mathrm{K}}\right) - C_y$$

In this model the abundance indices were assumed to be directly proportional to the stock abundance. The deterministic observation equation is:

$$I_{j,y} = q_j B_y$$

where qj is the constant of proportionality for the abundance index j and Ij,y the observed abundance index j in year y.

The management parameters of interest of the Schaefer model are summarized in Table 1.

THE CHOICE OF A STATE-SPACE MODEL

In recent years, Bayesian State Space modelling has been used more often in fish stock assessment (Meyer and Millar, 1999; Millar and Meyer, 2000).

The state-space approach modelling framework is highly flexible (Rivot *et al.*, 2004) and allows for deviations from model predictions (i.e., random variability) in both the data (measurement of relative biomass obtained from catch rates of commercial and/or research fishing) and in the unobserved state of the system of interest (e.g., annual population biomass) (Millar and Meyer, 2000) within a single consistent probabilistic framework (Rivot *et al.*, 2004).

Fisheries modellers tend to choose multiplicative lognormal errors (Millar and Meyer, 2000), which is what we use in our model.

The stochastic form of the process equations is:

$$\log\left(B_{y+1}\right) = \log\left(B_y + rB_y\left(1 - \frac{B_y}{\mathrm{K}}\right) - C_y\right) + \varepsilon_{process} \text{ where } \varepsilon_{process} \sim \mathrm{Normal}\left(0, \sigma^2_{\mathrm{process}}\right)$$

and the stochastic form of the observation equations is:

$$\log\left(I_{j,y}\right) = \log\left(q_j\right) + \log\left(B_y\right) + \varepsilon_{obs,j} \text{ where } \varepsilon_{obs,j} \sim \mathrm{Normal}\left(0, \sigma^2_{\mathrm{obs},j}\right)$$

$\varepsilon_{process}$ and $\varepsilon_{obs,j}$ are i.d.d. random variables.

To avoid problems of slow mixing due to the state space implementation of the Schaefer surplus production model in WinBUGS (Spiegelhalter *et al.*, 2002), we used the states $P_y = B_y/\mathrm{K}$ rather than B_y (Millar and Meyer, 2000). These new states are the ratio of biomass to carrying capacity, and upon replacing B_y by $\mathrm{K}*P_y$ the state equations become:

$$\log\left(P_{y+1}\right) = \log\left(P_y + rP_y\left(1 - P_y\right) - \frac{C_y}{\mathrm{K}}\right) + \varepsilon_{process}$$

and the observation equations become:

$$\log\left(I_{j,y}\right) = \log\left(q_j\mathrm{K}\right) + \log\left(P_y\right) + \varepsilon_{obs,j}$$

PRIORS USED FOR THE PRODUCTION MODEL PARAMETERS

As input priors, the model required: the probability distribution for the maximum intrinsic rate of increase, r, the average unfished stock size or carrying capacity, K, the constant of proportionality for the abundance index j, q_j, the ratio of the initial biomass (biomass at the first year of the time series considered) to the carrying capacity, p_0, the observation error standard deviation, $\sigma_{\mathrm{obs},j}$ and the process error standard deviation, $\sigma_{\mathrm{process}}$.

Priors for K, q_j, p_0, $\sigma_{obs,j}$ and $\sigma_{process}$

Preliminary analysis: A preliminary analysis was conducted where a deterministic SPM was fitted to abundance indices in Excel. This analysis permitted the exploration of the information contained in the available data about model parameter values.

Definition of priors for surplus production modelling: The prior for K was first assumed to be uniform over a large range of values between 0.1 tonnes and 150000 tons in order to enable equal credibility for small and large possible values for K. The upper bound was set at about three times the pre-fishery stock biomass estimates of assessed US lingcod (Jagielo and Wallace, 2005). However, this uniform prior on K appeared to be not a good choice as noticed in Millar and Meyer (2000). In this case, the model generated bimodal posterior distributions and failed convergence diagnostics with the uniform prior distribution of K, and did so even with a uniform prior over the log of K. The values of 2000 and 150000 tons were taken to be 5 and 95 percentile points (respectively) of a normal distribution over the log of K These percentiles equate to a normal random variable with mean and standard deviation of 9.8 and 1.3 (respectively) on the log scale.

The standard deviation of $\varepsilon_{process}$, $\sigma_{\mathrm{process}}$, was set at 0.05 (to account for large uncertainty in stock dynamics processes).

The standard deviation of $\varepsilon_{obs,j}$, $\sigma_{\mathrm{obs},j}$, was assumed to be equal to the values found in the preliminary analysis (Table 2).

The prior pdf for q_j is uniform over the log of q_j over the interval [-20,200]. This prior is the same for each abundance index *j*. The assumption of proportionality between the abundance indices and the stock biomass may not be accurate because of potential long term changes in catchability and variation of catchability with stock size (McAllister *et al.*, 2001). We tried fitting a simple hyperstability model for commercial CPUE data but found that this could not be made to work with the given catch time series and other relative abundance data. We considered the following as an alternative hypothesis: the ability of fishermen to catch lingcod, i.e., fishing power per unit effort, has improved annually since 1955 for each area. We considered that this rate of increase parameter (*tech*) for the increase in the efficiency of fishermen equalled the values found in the preliminary analysis (see Table 3).

1927 is the first year of the total catch time series considered. At this time the offshore trawl fishery in the late 1920s was not widely developed yet. The offshore lingcod stock biomass in 1927 (B_{1927}) was considered to be at un-fished conditions. The prior for p_0 is assumed to be log-normal with a mean of log(1) and a SD of 0.05.

Prior for the maximum rate of increase

Methodology: The prior on the intrinsic rate of increase (r) was obtained using a method that uses demographic data for the stock of interest. This method permits formulation of an informative prior on r. The use of such prior information is important because the

values assumed for r can strongly determine the ability of a population to recover if it has been heavily depleted (McAllister *et al.*, 2001) and the construction of informative priors is desirable wherever possible because it can help to improve estimation performance (McAllister *et al.*, 1994).

The demographic method used to construct an informative prior distribution for r was defined in McAllister *et al.* (2001) and reformulated in McAllister *et al.* (2008). The intrinsic rate of increase can be approximated with the Euler-Lotka demographic method (McAllister *et al.*, 2001). This method consists in a discrete approximation of an integral over ages 0 to infinity. The Lotka equation is numerically solved for r with the integration over ages starting at age 0. Assuming that there is no reproduction in the first year, a computation in which the integration starts at age 1 is analytically equivalent to an integration starting at age 0 (McAllister, 2008):

$$1 = \sum_{t=1}^{t_p} l_t m_t e^{-tr}$$

where l_t is the survivorship at age t, i.e., the fraction of animals surviving from age 1 to age t, m_t the number of age 1 recruits expected to be produced by adult females of age t, r the intrinsic rate of increase and t_p the age of the plus group, which is considered to be equal to 30 years for lingcod. At this age only 0.3% of the animals are still alive.

<u>Inputs parameters</u>: All the inputs parameters are random variables so that uncertainty is included in most of the input parameters.
The survivorship was computed with the following equation:

$$l_t = l_1 \exp\left(-\sum_{i=1}^{i-1} M_i\right)$$

where $l_1 = 1$ and M is the natural mortality rate for lingcod. We used as a reference case value for the natural mortality rate for females (M) the value used by Leaman and McFarlane in the last stock assessment for lingcod in 1997 (0.193 yr^{-1}). This estimate is based on Hoenig's (1983) relationship between maximum age and natural mortality and maximum observed ages of 23 years for females. This value was taken as the median of the lognormal probability distribution of M prior, with a standard deviation of 0.2. 10000 random values of M were generated from this lognormal distribution. M was assumed to be the same for each age.

The number of age 1 recruits expected to be produced by adult females of age t (m_t) is the product of the number of age 1 recruits produced per ton of spawners when spawner abundance approaches zero (R_s), the weight at age t (W_t), and the fraction mature at age t ($fmat_t$):

$$m_t = R_s W_t fmat_t$$

W_t and $fmat_t$ were taken as random variables. The program used the posterior means and covariances for the female growth parameters and the posterior modes and covariances

for the female length to weight conversion and the maturity parameters. It was assumed that the first age-at-maturity for females was the first observed age-at-maturity in the data set. The covariance matrix for each group of parameters was transformed into a Cholesky matrix for simulating random variable from the joint posterior distribution. 10000 random values were generated from the joint posterior distribution of each category of parameters from a Monte Carlo simulation. The joint posterior distribution was approximated by a multivariate student distribution with 500 degrees of freedom so that it might tend to a normal distribution.

The predicted lengths from age 1 to maximum age for lingcod for each area were computed using the growth parameters of the joint posterior distribution. The predicted weights from age 1 to maximum age were deduced from the length to weight conversion parameters drawn from their joint posterior distribution and the length at age predicted. The predicted fraction mature from age 1 to maximum age was calculated using the maturity parameters drawn from their joint posterior distribution. The maximum age for lingcod was assumed to be 50 years (the predicted survivorship at 50 years is less than $7*10^{-5}$).

In case of a Beverton & Holt relationship:

$$CR = \frac{4h}{1-h}, \text{ therefore: } R_s = \frac{4h}{S(1-h)} \text{ (Dorn, 2002),}$$

in case of a Ricker relationship:

$$CR = (5h)^{5/4}, \text{ therefore: } R_s = \frac{(5h)^{5/4}}{S} \text{ (Michielsens and McAllister 2004),}$$

where CR is called the Compensation Ratio or the expected number of age 1 recruits produced per unit mass of female spawners, h is the recruitment steepness and S is the spawner biomass produced per single age 1 recruit:

$$S = \left(\sum_{t=1}^{t_p-1} \left(W_t fmat_t e^{-tM} \right) \right) + W_{t_p} fmat_{t_p} \frac{e^{-t_p M}}{1-e^{-M}}$$

Where t_p is the age of the plus group and W_{tp} the expected weight of animals in the plus group. The weight of animals in the plus group (W_{tp}) was computed from the relative number (*nagep*) and weight (W) of animals in ages above the plus group. For t equals 30 to 50 years,

$$nagep_t = \frac{e^{-M(t-30)}}{\sum_{i=30}^{50} e^{-M(i-30)}}$$

$$W_{t_p} = \sum_{t=30}^{50} nagep_t W_t$$

The steepness (*h*) is defined as the ratio of recruitment at 20% of the unexploited stock biomass to recruitment in the un-fished state (Hilborn and Liermann, 1998). Steepness is therefore related to the maximum reproductive rate of a stock and is thus a measure of how productive a stock is at low population size (Myers *et al.*, 2002). Steepness is a meaningful productivity parameter (Forrest *et al.*, In Review), that is comparable between populations unlike the survival rate at low population size (Michielsens and McAllister, 2004). Steepness can be obtained through a hierarchical analysis of stock-recruit data (Michielsens and McAllister, 2004). Forrest *et al.* (In Review) obtained a posterior predictive distribution for steepness in Bayesian hierarchical meta-analysis for 14 populations of Pacific rockfish (*Sebastes spp.*) under Beverton & Holt (mean steepness = 0.71, CV = 0.22) and Ricker (mean steepness = 0.93, CV = 0.31) recruitment hypothesis. Ricker recruitment seems to be the most accurate assumption for lingcod compared to Beverton & Holt recruitment mainly because of the cannibalistic behaviour of this species which is an important source of juvenile mortality (Cass *et al.*, 1990; Beaudreau and Essington, 2007; A. Beaudreau, pers. commn.). Indeed Ricker recruitment predicts stronger density dependence within a fish population with decreasing recruitment when the spawning biomass is high. To our knowledge, no other hierarchical analyses have computed usable output distributions for the Ricker steepness parameter.

We could not directly use the posterior predictive distribution for steepness obtained from the Forrest *et al.* (In Review) hierarchical analysis of Pacific rockfish stock-recruit data to formulate a prior for *h* for lingcod. Rockfishes are groundfish species found in similar habitats to lingcod, many of which are also piscivorous like lingcod. However, rockfishes may generally have lower rates of growth and natural mortality compared to lingcod. In comparison to other groundfish, lingcod is more like a Pacific cod than a rockfish. Yet there were no other potentially suitable meta-analyses from which to obtain an informative prior for the Ricker steepness parameter for lingcod.

Jagielo and Wallace (2005) used a steepness of 0.9 for lingcod in a Beverton and Holt (B&H) relationship, but the prior assessment in 2004 used 0.7. Martell (1999) used 0.8. Myers *et al.* (1999) found a median steepness of 0.84 for Atlantic cod and a median steepness of 0.77 for Hexagrammidae. Therefore potential B&H steepness values for lingcod and lingcod-like species ranges from 0.7 to 0.9. We chose a middle value of 0.8 for steepness under B&H hypothesis for lingcod. We replaced the central tendency of the posterior predictive distribution for B&H steepness obtained for rockfish so that mean steepness is equal to 0.8 instead of 0.71.

The steepness value for the Ricker model is in average 1.5 times higher than that for the B&H model when the results come from a meta-analysis (Table 4). We assumed that the mean Ricker steepness for lingcod was 1.2. We updated the central tendency of the posterior predictive distribution for Ricker steepness obtained for Rockfish so that mean steepness is equal to 1.2 instead of 0.93.

We used the mean of the CVs of the two available posterior predictive distributions for the Ricker steepness parameter, that is CV=0.465, to summarize the uncertainty in this parameter. The updated posterior predictive distribution for rockfishes conforms to a Beta distribution. The two shape parameters of the beta distribution, *alpha* and *beta*, were estimated by renormalizing the updated posterior predictive distribution for steepness so that the minimum is 0 and maximum is 1 and then fitting a beta density function to the discretized renormalized histogram for steepness. The theoretical limit for h under Ricker recruitment is infinity but there appears to be a natural constraint on its value (Forrest *et al.*, In Review). In fitting a beta density function to the updated posterior predictive distribution of Ricker steepness, the value of 208 was the best fitting upper limit for h under Ricker recruitment.

The reference case probability distribution for h chosen for lingcod was a Beta distribution with *alpha* of 3.191 and *beta* of 661.534. 10000 random values of h between 0 and 1 were generated from this Beta distribution. Then these values were transformed so that the Ricker steepness may be contained in the interval [0.2; 208] (Figure 1):

$$h = h'(208 - 0.2) + 0.2$$

where $h' \in [0;1]$ and $h \in [0.2;208]$.

Output parameter: the intrinsic rate of increase: A random vector of values of r was thus obtained from the posterior distributions for the growth, length to weight conversion and maturity parameters and from the probability distribution of natural mortality and steepness parameters from a Monte Carlo algorithm. A frequency distribution of the resulting values for r was constructed. Finally a parametric density function was constructed based on the empirical distribution generated in the previous steps.

Sensitivity analyses: In Bayesian stock assessment, it is common to evaluate the sensitivity of results to alternative probability distributions for model input parameter (McAllister *et al.*, 2001).

In order to analysis the sensitivity to M, two tests were done: (a) assuming that the probability distribution of M is lognormal with a median of 0.250 (according to Walters and Bonfil, 1999) that is 30% upper than 0.193, and a standard deviation of 0.2, and (b) assuming that the probability distribution of M is lognormal with a median of 0.135 that is 30% lower than 0.193, and a standard deviation of 0.2.

In order to analyze the sensitivity to h, three different tests were done: (1) comparing the influence of a Beverton & Holt and a Ricker steepness, (2) comparing the influence of Ricker steepness with different Beta parameters assuming a mean h 25% lower than the reference mean h and a mean h 25% higher than the reference mean h, and (3) comparing the influence of Ricker steepness with different upper limits (max h = 104 i.e. the half of the reference case maximum, and max h = 416 i.e. the double of the reference case maximum) (Table 5).

DATA USED FOR THE STOCK ASSESSMENTS

Catch series

Surplus production models require only time series of catches and relative biomass indices and are for this reason commonly used in fisheries assessment (Meyer and Millar, 1999). Long time series of total catch biomass data for lingcod were compiled from 1927 to 2008, for area 3C, 3D, 5AB and 5CDE, based on historic trawl and hook and line records provided by Fisheries and Oceans Canada (DFO). DFO provided as well commercial annual catch for Canada, U.S., U.S.S.R, Japan and Poland trawl fishery from 1951 to 2008 and for hook and line fisheries from 1951 to 2008. The longline fisheries catching lingcod include the lingcod and dogfish (*Squalus acanthius*) fishery, the outside rockfish (*Sebastes sp.*) fishery and the halibut (*Hippoglossus stenolepis*) fishery. Finally, incomplete catch data series were provided from the recreational fishery in number of fish for each area. For each area, the missing catch records were filled assuming a linear evolution of the catch from 1927 to 1970 starting at 0 catch for 1927. The creel catch data available in King and Surry (2000) allowed us for filling the missing years between 1990 and 1994 for area 3C. The mean of the catch data available between 1970 and 2008 was used to fill the missing data between these two dates. The recreational fishery has been quite active in various west coast locations since 1970 (P. Starr pers. commn.). The catch records were converted from pieces to kg assuming average weight of 1.6 kg per fish as used in Leaman and McFarlane (1997).

Abundance indices series

The stock assessment model was fitted to different types of relative abundance data depending of the stock of interest.

Commercial CPUE indices: Qualified catch per unit effort (CPUE) was obtained from Canadian trawl fishery data for each of the four areas. Qualified CPUE (in kg/h) is determined from interviewed trawl landings between May-September for vessels using double gear (i.e., gear suspended from a double cable), and for which lingcod accounted for at least 25 % of the total catch weight. Cass *et al.* (1990) suggested that only those landings which occur during May-September should be used, as the trawl fishery is highly seasonal (between 1954 and 1999, 84% of the Canadian lingcod catch occurred during this period (King and Surry, 2000)). Moreover this period choice reduced any temporal bias introduced by the unavailability of male lingcod during winter (90% of the winter catch are composed of females (J. King, pers. commn.)). The use of 25 % qualified data was arbitrary and allowed the removal of observations of incidental capture of lingcod from consideration in the relative index series (Leaman and McFarlane, 1997). These data extended from 1954 to 2008. These series showed no apparent trend in the first years and were highly variable in the first years for area 5CDE. All these series showed a slight increase since the last decade. Because of the significant management changes which occurred in the groundfish fishery in 1996, we had to consider the commercial CPUE series as two time series: one from 1954 to 1995 and the second one from 1996 to 2008 with two different catchability parameters for each series.

Triennial Surveys indices: The U.S. National Marine Fisheries Service (NMFS) Triennial Trawl Surveys supplied tow-by-tow data for area 3C from 1980 to 2001 at a frequency of every 3 years with 1986 missing. Lingcod catch weight, distance fished and net width were provided allowing for the calculation of the area swept by the tow. For each year a CPUE was computed in kg per km^2. We used the Canada Vancouver compiled part of the data set that included only Canadian locations and excluded all U.S. locations. The raw data records were processed by Paul Starr to obtain a random stratified annual swept area biomass estimate for the available years. This series showed a decrease in abundance.

Shrimp Survey indices: Two series of abundance index were obtained from the West Coast Vancouver Island Shrimp Survey conducted by DFO, including area 3C and 3D. These data extended from 1975 to 2008 with 1984 and 1986 as missing years for both areas. These series showed a global decrease over the years. The series was highly variable in area 3C and showed an increase since the mid-1990s in this area. The Queen Charlotte Sound Shrimp Survey provided an index of abundance in area 5AB for 1999 to 2008 which showed a slight decrease in abundance.

Synoptic Survey indices: The West Coast Vancouver Island Synoptic Survey including area 3C and 3D conducted by DFO provided two series of abundance index for these two areas in years 2004, 2006 and 2008. These series showed a decline in both areas. The Queen Charlotte Sound Synoptic Survey conducted by DFO provided an abundance index for area 5AB in years 2003, 2004, 2005 and 2007. This series also showed a decrease. The Hecate Strait Synoptic Survey conducted by DFO provideed an abundance index for area 5CDE in years 2005 and 2007.
The triennial, shrimp and synoptic survey indices are relative biomass indices in kg or tons.

Multispecies Assemblage Survey indices: The Hecate Strait Multispecies Assemblage Survey conducted by DFO provided an abundance index for area 5CDE for the years 1984, 1987, 1989, 1991, 1993, 1995, 1996, 1998, 2000, 2002, 2003. This series showed a very slight decrease.

Creel Survey indices: The Creel Surveys conducted by DFO provided an abundance index in number of fish per 100 hours fishing for area 3C and area 3D for the years 2003 to 2008 and 2002 to 2008 respectively. These series showed an increase in area 3C and a decline in area 3D. These indices were not used as abundance indicators because they were judged to potentially reflect shifts in species targeting and not necessarily shifts in relative abundance of lingcod.

Longline Survey indices: Another series of abundance index was obtained from the International Pacific Halibut Commission (IPHC) Longline Surveys conducted on offshore waters of B.C. for the 4 areas of interest. This index extended from 1993 to 2008. Only data post 1997 were actually used. These data were indeed the most consistent in location, methodology and sampler training. Ineffective stations due to things such as heavy shark depredation, whale depredation and gear issues were not taken

into account in the annual mean abundance index computation. For each station the abundance index was computed as the ratio of the lingcod catch weight to the number of hooks retrieved. For each year a mean abundance index was computed in kg per hooks retrieved and CVs were computed. The stock assessment model was actually not fitted to the series obtained from the IPHC longline. Indeed these series showed an exponential increase of the biomass in each area which seemed to be inconsistent compared to the other series of abundance index which showed a decline or no significant trend or a very small increase in the biomass. Moreover the CVs obtained for this series were very large. Bait competition between Pacific halibut (*Hippoglossus stenolepis*), lingcod, spiny dogfish (*Squalus acanthias*) and other species and hook saturation issues may occur. But competition data were not available, so a readjustment was not undertaken.
Finally we used 5 abundance indices series for area 3C and 4 abundance indices series for the three other areas.

PROBABILITY MODELS FOR THE ABUNDANCE INDICES

In the likelihood function the data were assumed to be log-normally distributed:

$$I_{j,y} \sim \text{lognormal}\left(\ln\left(q_j B_y\right), \sigma^2_{\text{obs},j}\right)$$

Where $I_{j,y}$ is the observed index of abundance for series j in year y, q_j is the constant of proportionality for series j and $\sigma_{\text{obs},j}$ is the standard deviation in the error deviation between the log predicted index and the log observed index j.

METHOD TO OBTAIN POSTERIORS OF THE PRODUCTION MODEL PARAMETERS

We used a Markov Chain Monte Carlo method, i.e., Gibbs sampling implemented in WinBUGS software to carry out the Bayesian integration (Spiegelhalter *et al.*, 2002). In a Markov Chain, the value of each random number is conditional on the previous number. As a result, successive values drawn from the Markov chain may be correlated, which has some important consequences. The first is that the initial values that are used in the Markov chain may influence the results until a sufficiently large number of samples is generated. That is why it may be necessary to discard some of the initial samples as a 'burn in' (McCarthy, 2007). According to Gelman and Rubin diagnostic (1992), a burn-in of 10000 iterations was removed. The Heidelberger and Welch test allowed us to determine the number of iterations to keep after the Markov chain had reached "stationarity". This test is a run length control diagnostic based on the MC error (Monte Carlo standard error of the mean) which is a criterion of relative precision for the estimate of the mean. The MC error of all estimated parameter was less than 5% of the posterior SD after 500000 iterations. In order to keep the resulting computer files at a manageable size, a thinning of 50 was used. That is, only every 50th sample was saved, resulting in 10000 samples from each run being written to disc.

OUTPUT STATISTICS COMPUTED

The key output statistics computed included marginal posterior distributions of current stock biomass (B_{2009}), current stock biomass to carrying capacity (B_{2009}/K), current stock biomass to stock biomass at MSY (B_{2009}/B_{MSY}), the replacement yield (RepY), the ratio of the replacement yield in 2009 to the catch biomass in 2009 ($RepY_{2009}/C_{2009}$), and the ratio of fishing mortality rate in 2009 to fishing mortality rate at MSY (F_{2009}/F_{MSY}). The probability that stock biomass in 2009 exceeded stock biomass at MSY and the probability that the catch in 2009 exceeded the replacement yield were also computed. The marginal prior and posterior pdfs of r, K, and q_j were plotted to show the extent to which priors were updated.

SENSITIVITY TESTS (EFFECTS OF PRIORS ON THE STOCK STATUS)

In order to evaluate the effect of the model assumptions on the stock status and projections results, six different sensitivity tests were run for area 3C. We computed the Deviance Information Criterion (DIC) (Spiegelhalter *et al.*, 2002) for the reference and each sensitivity runs in order to compare the relative goodness of fit to the data and parsimony of the different models. The model with the smallest DIC was estimated to be the model that would best predict new sets of observed data. When the difference in DIC between models was more than five, they were regarded to be significantly different as a rule of thumb (Spiegelhalter *et al.*, 2002).

Prior mean value for *r*

In order to evaluate the sensitivity of the model results to the informative prior for r, different priors of r were applied. The two first runs were based on the results obtained with a low and a high Ricker steepness. And because the Ricker steepness is a considerable assumption we made for the reference case, it was also convenient to test the sensitivity of the results to this assumption by running the stock assessment model with a Beverton and Holt steepness.

Rate of increase in the fishermen efficiency

We evaluated the sensitivity of the model to the setting of a unique rate of increase in the efficiency of fishermen (*tech*) by assuming first that this rate is equal to zero and then that this rate is different before and after 1996 (*tech1* and *tech2*) (Table 6).

Commercial CPUE series

We finally evaluated the sensitivity of the model to the distinction we made in the commercial CPUE series before and after 1996, by considering a unique commercial CPUE series.

Projections were done for 5, 20 (~ 1 generation) and 40 years (~ 2 generations) to evaluate the potential future stock trends resulting from alternative fixed TAC policies.

Stock biomass and the ratio of stock biomass to stock biomass at MSY were computed from 1927 to the final year of each projection as well as the probability that final stock biomass exceeds 40% of stock biomass at MSY, the probability that final stock biomass exceeds 80 % of stock biomass at MSY, the probability that final stock biomass exceeds stock biomass in 2009, and the probability that fishing mortality rate in 2009 exceeds final fishing mortality rate.

RESULTS

ESTIMATION OF THE GROWTH, LENGTH TO WEIGHT CONVERSION AND MATURITY PARAMETERS FOR EACH AREA

Estimation of the growth parameters

Females and males were very different in terms of growth (Figure 2). The results for the female growth parameters were similar for the four areas. The posterior mean of L_∞ was contained between 1141 mm and 1331 mm, K was contained in the interval [0.10 year^{-1}; 0.14 year^{-1}] and t_o was contained between -3.62 years and -1.97 years (Table 7). These estimations were quite precise according to the low CVs. Concerning the male results, the estimates of growth parameters were similar between the areas 3C and 5CDE and the areas 3D and 5AB. The posterior mean for L_∞ remained inferior to the female estimation which was consistent with the previous studies (Cass *et al.*, 1990, Jagielo and Wallace, 2005). The estimation for K for males was very low for the areas 3D and 5AB ($K = 0.09$ year^{-1}), compared to the estimation for area 3C (0.23 year^{-1}) and 5CDE (0.28 year^{-1}) with a high CV compared to the other areas (0.29 and 0.13 for area 3D and 5AB respectively) (Table 7). This difference was likely due to the lack of data for the lower ages for areas 3D and 5AB. It could be interesting to do a simple hierarchical model across the 8 populations (2 sex and 4 areas) to obtain a more precise estimation of K, by first testing the sex effect, then the area effect. But the estimation of L_∞ was quite precise, so it was not necessary to run such a model. Moreover only the estimation for the female was used for the definition of the r prior.

Estimation of the maturity parameters

The median age posterior mode for female lingcod ranged from 3.79 to 4.18 years (Table 8, Figure 3) which is consistent with the observation of Cass *et al.* (1990) who estimated that the mean age of mature female lingcod ranged from 3 to 5 years. The posterior mode for median age for male ranged from 3.52 to 3.79 years (Table 8) whereas Cass *et al.* (1990) estimated that most males were mature at age 2.

Estimation of the length to weight conversion parameters

The estimated parameters for female were very similar from one area to another. The intercept a ranged between 1.44E-09 and 2.08E-09. The length exponent b ranged between 3.227 and 3.285. The estimated parameters for male were also similar in between areas. The a parameter ranged between 7.28E-10 and 1.46E-09 and the standard

deviations were high for the areas 3D and 5AB. The *b* parameter ranged between 3.288 and 3.462 with higher standard deviation for areas 3D and 5AB (Table 9, Figure 4).

PRIOR DEFINITION FOR THE MAXIMUM RATE OF INCREASE

r prior

In order to find the best approximation of the frequency distribution of *r* values drawn from the Monte Carlo method to generate a prior density function for *r*, three different frequency distributions (lognormal, normal and gamma) were fitted to the results for area 3C. The sum square of deviation between the Monte Carlo frequency and the predicted frequency was minimized in each case so that the best fit was obtained for each distribution. Comparing the sum square between the three distributions, the approximation with the best goodness of fit was the normal one with a sum of squares of 11 378 instead of 31 435 and 69 474 respectively for the gamma and the lognormal distribution (Figure 5).

The prior distributions for *r* were very similar in between the different outside populations, centred on about 0.25 with very similar CVs of about 0.37 (Table 10, Figure 6).

Sensitivity runs

The *r* prior showed considerable sensitivity to the inputs of *M* (Table 11, Figure 7).

The *r* prior was particularly sensitive to the prior on steepness (Table 12, Figure 8).

The *r* prior was also sensitive to the upper limit of the Ricker steepness (Table 13, Figure 9).

CONDITION OF THE STOCKS

Stock status

The results of the stock assessment are only described for area 3C. For the results of the three other stocks assessments, see Appendix Table 15 and Appendix Figure 11.

The results of the reference case run are summarized in Table 14. The posterior mean for the intrinsic rate of increase *r* (0.231) was lower than the prior mean (0.249). The CV of the posterior (0.248) was lower than the prior CV (0.351). The decrease in mean value and decrease in CV suggest that the stock trend data provided some information on *r*. The posterior mean for the carrying capacity K was 22150 t with a CV of 0.253. The posterior median of K was 21040 t which is close to the mean indicating that the skew of the posterior for K is relatively low as for other biomass values. The posterior mean for B_{MSY} (11080 t) was half the value of the posterior mean for K due to the structure of the surplus production model. The posterior mean for MSY was 1205 t with a CV of 0.078. The

posterior means of the stock trend indices q_j were updated considerably from the uniform priors for $\log(q_j)$. The posterior mean and median for stock biomass in 2009 were 10590 t and 10100 t respectively. The posterior mean for B_{2009}/K was 49% and the posterior mean for B_{2009}/B_{MSY} was 97%. Stock size was therefore half of its un-fished size K and nearly the same as its B_{MSY} reference point. Stock biomass has shown a progressive decline since the late 1920s with the steepest decline between the early 1980s to the mid 1990s (Figure 10). The stock appears to have recovered with an increase in abundance since the late 1990s.

The posterior mean of F_{2009}/F_{MSY} was 0.756. The posterior mean for the replacement yield in 2009 (the amount that can be fished so that the stock will not increase or decrease in the next year) was 1144 t which is higher than the current TAC for area 3C (950 t). The posterior mean ratio of the total catch in 2009 to replacement yield was 73%. Finally, the probability that the biomass in 2009 exceeds B_{MSY} was 43%.

Sensitivity runs

The results of the sensitivity runs are summarized in Table 15. The estimates of B_{MSY} increased and decreased when the prior mean for r was decreased and increased from 11080 t to 12250 t and 10510 t respectively. The replacement yield was very slightly impacted by the change in the mean prior of r, i.e. it decreased from 1144 t to 1117 t when prior mean of r decreased and the replacement yield increased from 1144 t to 1151 t when prior mean of r increased. The estimate of B_{2009}/B_{MSY} was very slightly changed from 97% to 95% in the case of a low r, and to 100% in the case of a high r. The setting of two different *tech* parameters and the assumption of a unique catchability coefficient before and after 1996 for the commercial CPUE series impacted very slightly the estimates of B_{MSY}. The replacement yield in 2009 was slightly changed in the two cases with a mean of 1153 t in the case of 2 *tech* parameters and a mean of 1049 t in the case of a unique commercial CPUE series. The ratio B_{2009}/B_{MSY} was changed considerably if only one commercial CPUE series was considered (70% instead of 97% in the reference case.)

The assumption that the efficiency of fishermen did not increase over the years had the strongest impacts on the stock status results. In that case, most parameters were estimated with a very high CV exceeding 1. The posterior mean of B_{MSY} was 27270 t which is very high compared to the reference case posterior mean. The CV of B_{MSY} was very high under this hypothesis (1.069). The posterior mean of the replacement yield (718 t) was lower than for the reference case. The posterior mean of the ratio B_{2009}/B_{MSY} (1.809) was doubled compared to the reference case. The posterior mean and median of B_{2009} were estimated at 51720 t and 32380 t respectively with a very high CV of 1.167.

The assumption of a B&H recruitment changed the results very slightly for the replacement yield in 2009 and the ratios F_{2009}/F_{MSY}, B_{2009}/B_{MSY} and $C_{2009}/\mathrm{RepY}_{2009}$. Under this assumption, the estimates of B_{MSY} and B_{2009} were lower than in the reference case (9866 t and 9873 t respectively instead of 11080 t and 10590 t).

According to the DIC analysis, the model with the best goodness of fit to the data was the reference case. The model with two different tech parameters had a DIC equal to the reference case (Table 16). As the reference case was the most parsimonious model, we chose this one to assess the stock. The models with just one commercial CPUE and no tech parameter had significantly different DIC, much higher than the other models (1292 and 1210 respectively instead of 1195). These results show that it is important to take into account an increase in the efficiency of fishermen and to distinguish the commercial CPUE before and after 1996 in the model.

DISCUSSION

DATA USED

We considered four stocks of offshore lingcod in our analyses. This choice was based mainly on management areas and less on biological evidence for stock structure. For example, it is plausible that the population of lingcod in area 3C and 3D consists of one intermixing breeding population and could be assessed as such and the results later split out into separate prescriptions for the two management areas. Moreover fishing tows often overlap in both areas (King and Surry, 2000). However we followed the convention of previous lingcod assessments of treating these two areas as separate breeding populations. Even if the biological analysis results, especially in terms of growth and the patterns of the stock trend indices, show differences among the considered stocks, there is no obvious evidence of four separate stocks. The significance of the difference between the biological results (e.g., growth parameter estimates) for each area could be tested to determine if a biological differentiation is plausible among the four areas.

Some of the biological data were obtained from the commercial trawl landings. Growth rates of lingcod may be biased by the minimum size limit of the fishery, particularly for ages 2 to 4 years, and by the fact that the fishery does not occur on the juvenile rearing areas (ages 1 to 2 years). Samples from the hook and line fishery could provide bigger fish (i.e. older fish) data but there is no hook and line age structures at the moment.

The among-year variation in sampling is large (e.g., in area 3C the number of aged fish ranges from 1 in 2001 to 871 in 1979). A weighting algorithm for inputs could have been used in the biological parameter estimation models in order to control the influence of age data in fitting the model to the observations.

Regarding the maturity parameter estimation, the maturing and ripening (fish that are in the process of becoming mature or in the process of getting ready to spawn) individuals were considered as mature. Indeed in the data base the difference between maturing or ripening fish and resting fish (mature fish that have spawned and are in between spawning seasons) is not always specified because some observers are not able to see the difference when the measurements are done. Moreover if the maturing and ripening fish are excluded from the analysis, the fraction mature never comes close to 1. If the results for females are consistent with the previous estimates of the median age mature, the male median age mature seems to be overestimated in the four areas and this could be a

consequence of including fish that are incorrectly assumed to be mature in the estimation. An improvement in the maturity assignment protocol could help to reduce potential bias. Moreover, taking into account length and age together could provide a better prediction of lingcod maturation than either variant considered alone as recommended in Richards *et al.* (1990).

The use of CPUE obtained from the landings of trawl vessels using double gear was justified because they represented the majority of lingcod landings since the 1950s. The use of a 25% qualified CPUE may be not appropriate anymore because the fishery has changed a lot since 1996 mostly with the implementation of individual quotas. These changes resulted in substantially reduced effort in the trawl fishery accompanied by a rise in targeted effort in the hook and line fishery. The majority of the lingcod catch tends to occur out of the period May-September since 1996 (King and Surry, 2000), especially in areas 3C and 3D. Since this series is one which has the most influence in the data set, we recommend the more conventional generalized linear modeling of this CPUE series in future assessments so that the possible effects that could bias the series (like seasonal or depth effects) might be removed.

Concerning the recreational catch data, a mean weight of 1.6 kg per fish was applied to convert the catch from pieces to kg according to Leaman and MacFarlane (1997). However, there are no biological data available for the recreational fishery to evaluate the appropriateness of this mean weight (King and Surry, 2000).

ASSESSMENT MODEL

A simple state-space SPM model was used for the stock assessment. This model fitted most of the abundance index data reasonably well for all four populations. Catch-at-age data were available and an age-structured model will be conducted after this study.

The methodology included the formulation of an informative prior on r with some added refinements to its most recent application to boccaccio (McAllister, 2008). Unlike the previous application where only M and steepness were random variables, all the parameter inputs this time were random variables and a Ricker steepness parameter, rather than a Beverton & Holt steepness parameter, was assumed. We made the assumption of Ricker because lingcod are known to have a cannibalistic behaviour (Cass *et al.*, 1990; Beaudreau and Essington, 2007; A. Beaudreau pers. commn.). Nevertheless, since this assumption is a significant one, further study of the lingcod's diet in B.C. should be undertaken to better understand the degree and demographics of cannibalism of this population. The CVs of r are quite tight at about 0.37. This could be due to the fact that the CV chosen for M was too small. Moreover, a value of 0.193 was chosen for M according the value used in Leaman and McFarlane (1997) based on Hoenig's (1983) relationship. As r prior shows a considerable sensitivity to the value chosen for M, it would be appropriate to try other ways to estimate this parameter in the future. The SPM applied presumed that M at the lowest population density was unchanging over time. However, this parameter under low density conditions is likely to change over the years due to changes in food availability, predators or other environmental factors (Hilborn and Walters, 1992).

We assumed that the stock was near un-fished conditions in 1927. We could have evaluated the sensitivity of the stocks assessment models to the prior on p_0 by setting the mean of this prior to lower values. Indeed even if the lingcod fishery was not extended to offshore waters yet, lingcod catch could have occurred offshore. But this prior seems to have negligible influence on the stock status estimates (McAllister, 2008).

We supposed that the CPUE was proportional to the abundance of fish. However, when fishermen are highly efficient in their search for fish, they concentrate the effort on the areas where fish are most abundant, and fish tend to aggregate even when abundance decreases. That is why, even if abundance drops, the CPUE may stay high. This phenomenon in the CPUE-abundance relationship is called hyperstability (Hilborn and Walters, 1992).

In that case, $I_{com,y} = q_{com} B_y^{\lambda}$, where $0 < \lambda < 1$.

However our preliminary study in Excel showed that taking into account the hyperstability parameter (λ) does not improve the goodness of fit of the model to the data. Indeed the sum of log square deviations between observed and predicted abundance indices doubled when the hyperstability parameter was included in the model, compared to that when the model took into account a *tech* parameter.

The estimated rate of increase in the efficiency of fishermen is quasi null in area 3D (0.2%) compared to area 3C (3%) even though these two areas are adjacent. The *tech* parameter was essential to fit the model to the commercial CPUE. This parameter that we called rate of increase in the efficiency of fishermen could have in fact no technical sense but be necessary to correct the uncertain CPUE series. In that case the commercial CPUE would be more consistent in area 3D. However, interviewing a trawl fisherman indicated that fishermen cooperated much more and increased their efficiency much more in area 3C in recent years compared to area 3D. In fact, due to the much higher trawl quota in area 3C (800 t) than area 3D (220 t), trawl fishermen tend to target lingcod and cooperate with each other in area 3C in the summer. In contrast, due to the very low trawl lingcod quota in are 3D, trawl fishermen in the last decade have tended to cooperate to actively avoid lingcod in area 3D in the summer, the season that makes up the qualified CPUE data.

Because time was limited to carry out this assessment, the Gibbs sampler was chosen for the stock assessment model whereas McAllister used a SIR algorithm for the stock assessment of boccaccio in 2008. It could be interesting to evaluate whether the results of the assessment would differ with a SIR algorithm.

CONCLUSION

This study is the first to estimate biological parameters for lingcod using Bayesian statistics. We are quite confident in our estimations except in the case of the results for the growth parameter estimation for males in area 3D and 5AB and in the maturity parameters for males in the four areas. The intrinsic rate of increase (r) was estimated for

the first time assuming a Ricker recruitment steepness which appears to be more appropriate than and Beverton & Holt hypothesis given the known cannibalistic behaviour of lingcod.

Bayesian assessment is a novel approach in B.C. offshore lingcod assessments. This statistical framework allowed us to formulate an informative prior for r, for taking into account several data sources in the model and uncertainty in the process and the observations, and for conducting a risk analysis. The abundance of the stock in area 3C has been increasing since the late 90s and was very close to B_{MSY} in 2009, that is at about 50% of un-fished stock size. The implementation of a TAC of 950 t since 1998 allowed for the rebuilding of the stock.

Stock projections for the sensitivity runs in area 3C still need to be undertaken to evaluate the sensitivity of future trends of the stock to the different hypotheses made concerning r and the increase in the efficiency of fishermen. Moreover an age-structured model may be applied after this study. The estimation for the other stocks showed high posterior CVs in estimates of stock status. The stock biomass showed an increasing trend in area 5AB and 5CDE since the late 1990s.

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Table 1. Summary of management parameters of interest for the Schaefer model.

Maximum Sustainable Yield (MSY)	$rK/4$
Stock size for MSY	$K/2$
Rate of exploitation at MSY	$r/2$
Maximum rate of exploitation	r

Table 2. Standard deviation of the observation error for each abundance indices j, $\sigma_{obs,j}$, per area, obtained from the preliminary analysis and used in the assessment models. j=com1 for the Commercial CPUE series before 1996, j=com2 for the Commercial CPUE series after 1996, j=tri for the Triennial Survey series, j=sh for the Shrimp Survey series, j=sy for the Synoptic Survey series and j=multi for the Multispecies Assemblage Survey series. The area where the survey took place is given between parenthesis (WCVI= West coast Vancouver island, QCS= Queen Charlotte Sound, HS= Hecate Strait).

	$\sigma_{obs,com1}$	$\sigma_{obs,com2}$	$\sigma_{obs,tri}$	$\sigma_{obs,sh}$	$\sigma_{obs,sy}$	$\sigma_{obs,multi}$
3C	0.35	0.35	0.6	0.65 (WCVI)	0.65 (WCVI)	--
3D	0.35	0.45	--	1.1 (WCVI)	1 (WCVI)	--
5AB	0.3	0.2	--	1.5 (QCS)	0.3 (QCS)	--
5CDE	0.8	0.35	--	--	0.2 (HS)	0.4

Table 3: Values of the rate of increase in the efficiency of fishermen (*tech*) taken in the reference run per area.

	3C	3D	5AB	5CDE
tech (yr^{-1})	3%	0.2%	1.4%	1.4 %

Table 4: Steepness values obtained from meta-analysis under B&H and Ricker assumptions.

References	**Species**	**Mean B&H *h***	**Mean Ricker *h***	**Ratio** $\frac{h(\text{Ricker})}{h(\text{B \& H})}$
Forrest *et al.* (In Review)	Rockfish	0.71 (CV = 0.22)	0.93 (CV = 0.45)	1.31
Michielsens & McAllister (2004)	Baltic salmon	0.70 (CV = 0.23)	1.24 (CV = 0.48)	1.77

Table 5: Different steepness probability distributions tested in the sensitivity analyses.

Recruitment assumption	**Mean steepness**	**Steepness probability distribution**
B&H	0.8	Beta(9, 3)
Ricker		
med *h* (reference case)	1.2	Beta(3.191, 661.534)
low *h*	0.9	Beta(2.785, 825.872)
high *h*	1.5	Beta(3.446, 548.636)

Table 6: Summary of the sensitivity runs applied for area 3C. The values of the mean and SD of low *r*, high *r* and B&H *r* are presented in the results of the sensitivity of the prior for *r* to *h* (Table 12), the values of *tech1* (before 1996) and *tech2* (after 1996) are the values found in the preliminary analysis.

Sensitivity runs in area 3C	
1	low *r*
2	high *r*
3	B&H *r*
4	*tech1* (yr^{-1}) = 3% *tech2* (yr^{-1}) = 2%
5	*tech* (yr^{-1}) = 0
6	1 commercial CPUE

Table 7: Posterior means and CVs for the von Bertalanffy growth parameters for each sex and each area.

	3C		3D		5AB		5CDE	
Female	mean	CV	mean	CV	mean	CV	Mean	CV
Sample size	*5088*		*1303*		*4403*		*875*	
L_∞ (mm)	**1141**	0.01	**1245**	0.03	**1331**	0.02	**1254**	0.02
K (year^{-1})	**0.14**	0.05	**0.10**	0.09	**0.10**	0.05	**0.13**	0.07
t_0 (year)	**-2.17**	-0.08	**-3.62**	-0.11	**-3.30**	-0.06	**-1.97**	-0.15
Male	mean	CV	mean	CV	mean	CV	Mean	CV
Sample size	*2963*		*285*		*1534*		*123*	
L_∞ (mm)	**844**	0.01	**1012**	0.10	**1086**	0.05	**841**	0.02
K (year^{-1})	**0.23**	0.06	**0.09**	0.29	**0.09**	0.13	**0.28**	0.12
t_0 (year)	**-1.83**	-0.12	**-7.76**	-0.25	**-5.76**	-0.12	**-1.00**	-0.39

Table 8: Posterior modes and standard deviation of the maturity parameters for each sex and each area.

	3C		3D		5AB		5CDE	
Female	mode	SD	mode	SD	mode	SD	mode	SD
Sample size	*3339*		*1300*		*3434*		*875*	
med_age (year)	**4.17**	0.014	**3.79**	0.035	**4.18**	0.022	**3.79**	0.046
σ_{mat}	**0.329**	0.039	**0.357**	0.080	**0.493**	0.046	**0.360**	0.097
Male	mode	SD	mode	SD	mode	SD	mode	SD
Sample size	*1604*		*0*		*1098*		*123*	
med_age (year)	**3.79**	0.018	no data		**3.52**	0.045	**3.64**	0.060
σ_{mat}	**0.304**	0.054			**0.487**	0.086	**0.187**	0.260

Table 9: Posterior modes and SD of the length (mm) to weight (kg) conversion parameters for each sex and each area.

	3C		3D		5AB		5CDE	
Female	mode	SD	mode	SD	mode	SD	mode	SD
Sample size	*494*		*366*		*396*		*120*	
log(a)	-19.99	0.11	-20.36	0.16	-19.99	0.13	-20.29	0.06
a	**2.08E-09**	-	**1.44E-09**	-	**2.08E-09**	-	**1.54E-09**	-
b	**3.227**	0.017	**3.285**	0.024	**3.232**	0.020	**3.275**	0.01
Male	mode	SD	mode	SD	mode	SD	mode	SD
Sample size	*237*		*66*		*156*		*33*	
log(a)	-21.04	0.06	-20.35	0.45	-21.39	0.37	-20.57	0.07
a	**7.28E-10**	-	**1.46E-09**	-	**5.16E-10**	-	**1.16E-09**	-
b	**3.405**	0.009	**3.288**	0.070	**3.462**	0.057	**3.328**	0.012

Table10: Mean, SD and CV of r prior for each area.

	3C	3D	5AB	5CDE
Mean (r)	0.249	0.250	0.243	0.243
SD (r)	0.087	0.090	0.090	0.095
CV (r)	0.351	0.362	0.370	0.390

Table 11: Mean, SD and CV of r prior under different M prior, area 3C.

	Median (M)		
	0.135	**0.193**	**0.250**
Mean (r)	0.207	**0.249**	0.284
SD (r)	0.075	**0.087**	0.097
CV (r)	0.361	**0.351**	0.343

Table 12: Mean, SD and CV of r alternative priors under Ricker and Beverton & Holt recruitment, area 3C.

	Ricker			**B&H**
	low h	**med h**	**high h**	
Mean (r)	0.199	**0.249**	0.290	0.374
SD (r)	0.080	**0.087**	0.093	0.117
CV (r)	0.400	**0.351**	0.321	0.314

Table 13: Mean, SD and CV of r alternative priors under different Ricker upper limit assumptions, area 3C.

	Upper limit h Ricker		
	104	**208**	**416**
Mean (r)	0.161	**0.249**	0.364
SD (r)	0.064	**0.087**	0.111
CV (r)	0.398	**0.351**	0.304

Table 14: Posterior mean, SD, CV, 10th, 50th and 90th percentiles for key parameters and stock status indicators for B.C. offshore lingcod in area 3C.

Reference case	Mean	SD	CV	10th	Median	90th
K	**22150**	5610	0.253	16510	21040	29020
R	**0.231**	0.057	0.248	0.158	0.230	0.305
MSY	**1205**	94	0.078	1087	1211	1316
B_{2009}	**10590**	3211	0.303	7106	10100	14510
B_{1927}	**22190**	5737	0.259	16340	21070	29260
B_{2009}/K	**0.485**	0.114	0.235	0.342	0.478	0.636
C_{2009}/MSY	**0.689**	0.060	0.087	0.626	0.681	0.759
F_{2009}/F_{MSY}	**0.756**	0.218	0.288	0.522	0.717	1.035
B_{2009}/B_{MSY}	**0.969**	0.222	0.229	0.687	0.958	1.266
C_{2009}/RepY$_{2009}$	**0.730**	0.090	0.124	0.646	0.712	0.833
B_{MSY}	**11080**	2805	0.253	8255	10520	14510
RepY$_{2009}$	**1144**	118	0.103	989	1157	1277
q_com1	**1.69E-02**	0.0043	0.256	1.14E-02	1.67E-02	2.26E-02
q_com2	**1.23E-02**	0.0039	0.316	7.73E-03	1.18E-02	1.74E-02
q_sh	**7.11E-02**	0.0199	0.280	4.66E-02	6.96E-02	9.75E-02
q_sy	**1.60E-01**	0.0803	0.501	7.85E-02	1.44E-01	2.63E-01
q_tri	**5.49E-04**	0.0002	0.362	3.19E-04	5.23E-04	8.06E-04
p(B_{2009}>B_{MSY})	**0.428**	--	--	--	--	--
p(C_{2009}>RepY$_{2009}$)	**0.015**	--	--	--	--	--

Table 15: Posterior mean, CV, median and 80% credibility intervals for 7 parameters for the reference run and the 6 sensitivity runs.

		ref case	low *r*	high *r*	B&H *r*	0 tech	2 tech	1 cpue
B_{MSY}	**Mean**	**11080**	**12250**	**10510**	**9866**	**27270**	**10690**	**11600**
	CV	0.253	0.286	0.244	0.260	1.069	0.243	0.269
	10^{th}	8255	8879	7877	7313	10380	7996	8515
	Median	10520	11500	10020	9356	17970	10180	10950
	90^{th}	14510	16320	13650	12930	52650	13990	15420
B_{2009}	**Mean**	**10590**	**11540**	**10380**	**9873**	**51720**	**10660**	**8078**
	CV	0.303	0.360	0.293	0.301	1.167	0.296	0.305
	10^{th}	7106	7408	7015	6656	16910	7223	5548
	Median	10100	10820	9983	9467	32380	10190	7644
	90^{th}	14510	16260	14150	13350	105000	14660	11020
$\mathbf{RepY_{2009}}$	**Mean**	**1144**	**1117**	**1151**	**1162**	**718**	**1153**	**1049**
	CV	0.103	0.115	0.104	0.104	1.034	0.101	0.132
	10^{th}	989	949	998	1007	0.0001	1003	865
	Median	1157	1134	1169	1181	696	1168	1061
	90^{th}	1277	1263	1285	1295	1277	1283	1217
F_{2009}/F_{MSY}	**Mean**	**0.756**	**0.793**	**0.725**	**0.706**	**0.232**	**0.717**	**1.050**
	CV	0.288	0.309	0.298	0.301	0.540	0.287	0.242
	10th	0.522	0.531	0.498	0.485	0.073	0.498	0.768
	Median	0.717	0.747	0.683	0.664	0.227	0.678	1.010
	90th	1.035	1.112	1.003	0.976	0.393	0.990	1.382
B_{2009}/B_{MSY}	**Mean**	**0.969**	**0.951**	**1.002**	**1.017**	**1.809**	**1.010**	**0.703**
	CV	0.229	0.239	0.234	0.234	0.120	0.226	0.196
	10th	0.687	0.666	0.703	0.713	1.530	0.715	0.533
	Median	0.958	0.941	0.994	1.009	1.816	1.004	0.693
	90th	1.266	1.254	1.315	1.336	2.074	1.310	0.885
$C_{2009}/\mathbf{RepY_{2009}}$	**Mean**	**0.730**	**0.750**	**0.725**	**0.719**	**1538000**	**0.724**	**0.801**
	CV	0.124	0.139	0.130	0.134	2.088	0.120	0.154
	10th	0.646	0.653	0.641	0.637	0.646	0.643	0.677
	Median	0.712	0.727	0.705	0.698	1.185	0.706	0.777
	90th	0.833	0.869	0.826	0.819	8243000	0.822	0.953

Table 16: DIC values for the 6 runs.

	Ref case	low *r*	high *r*	B&H *r*	0 tech	2 tech	1 cpue
DIC	**1195**	1197	1195	1196	1210	1195	1292

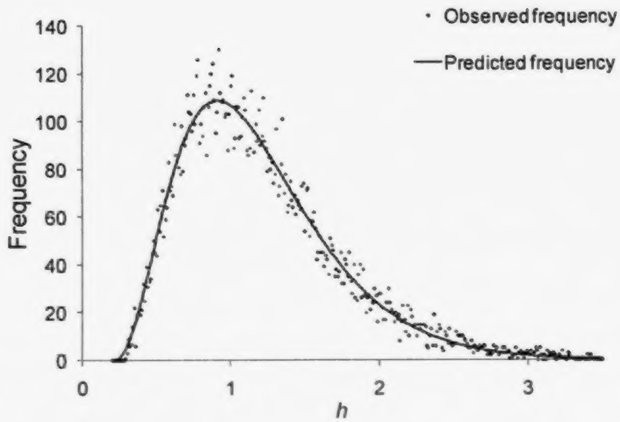


Figure 1: Plot of the observed steepness from Forrest *et al.* (In Review) updated so that mean $h = 1.2$, and of the fitted Ricker steepness Beta distribution.

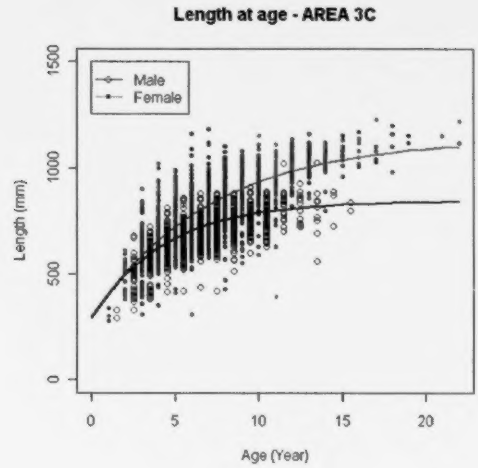


Figure 2: Plots of the observed length at age in AREA 3C for both female (red) and male (blue) and the von Bertalanffy curves fitted to the data.

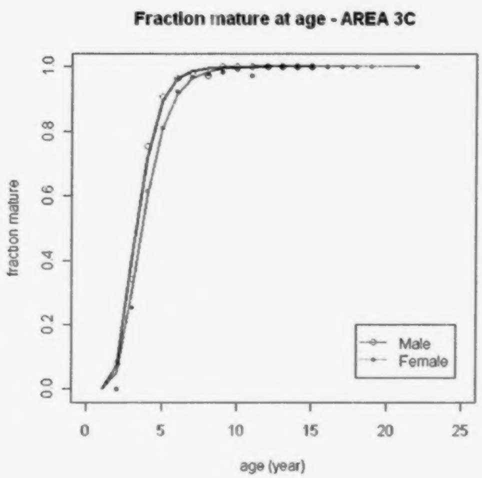


Figure 3: Plots of the observed fraction mature at age in AREA 3C for both female (red) and male (blue) lingcod and the cumulative lognormal curves fitted to the data.

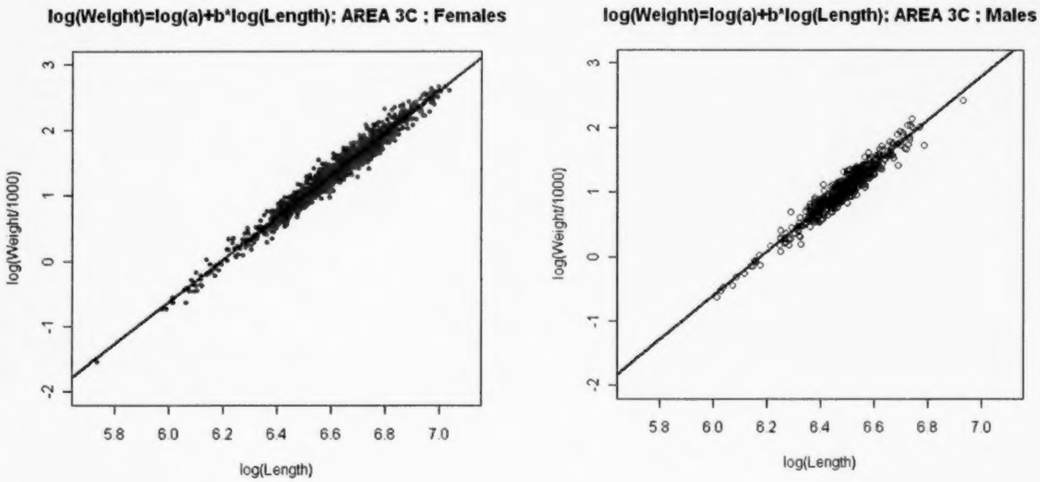


Figure 4: Plots of the observed length and weight at age in AREA 3C without outliers for both female (red, on the left) and male (blue, on the right) lingcod and the curves ($\log(W_t) = \log(a) + b^*\log(L_t)$) fitted to the data.

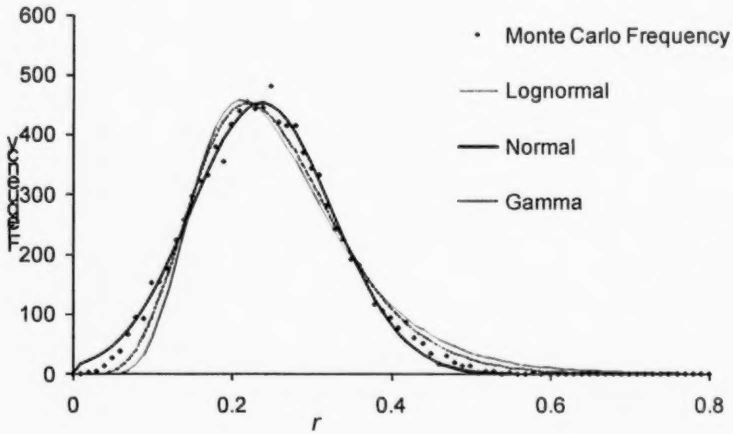


Figure 5: Plot of the frequency distribution of r values drawn from the Monte Carlo method and the best lognormal, normal and gamma approximations.

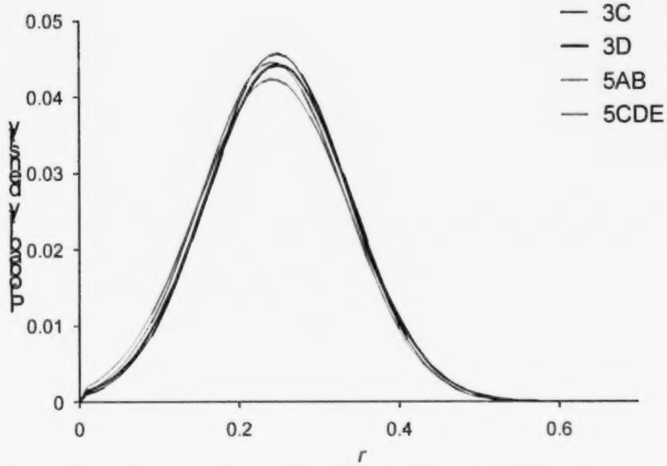


Figure 6: Prior normal distributions for *r* for lingcod in the four areas.

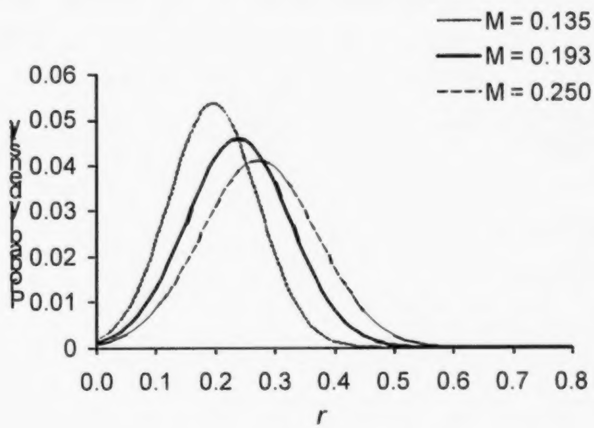


Figure 7: Alternative *r* prior normal distributions for lingcod in area 3C under different assumptions on median (M).

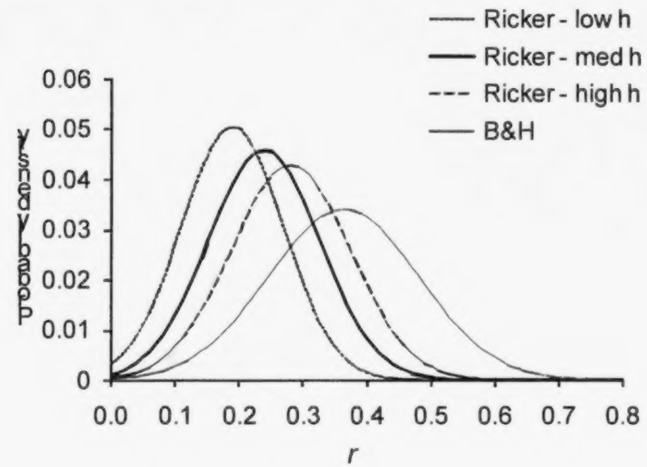


Figure 8: Alternative r prior normal distributions for lingcod in area 3C under different assumptions on h.

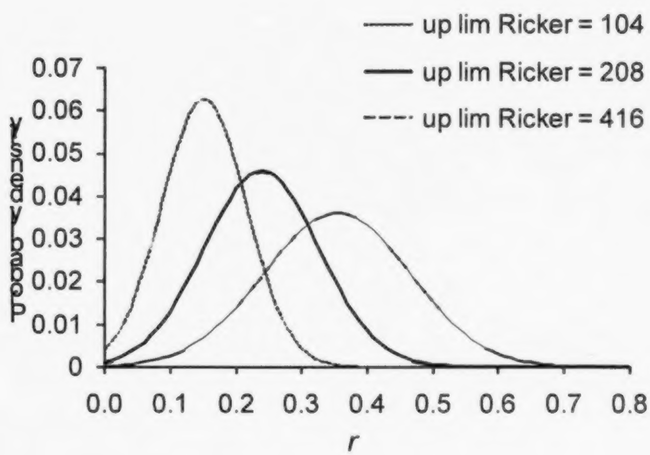


Figure 9: Alternative r prior normal distributions for lingcod in area 3C under different assumptions on the upper limit of Ricker.

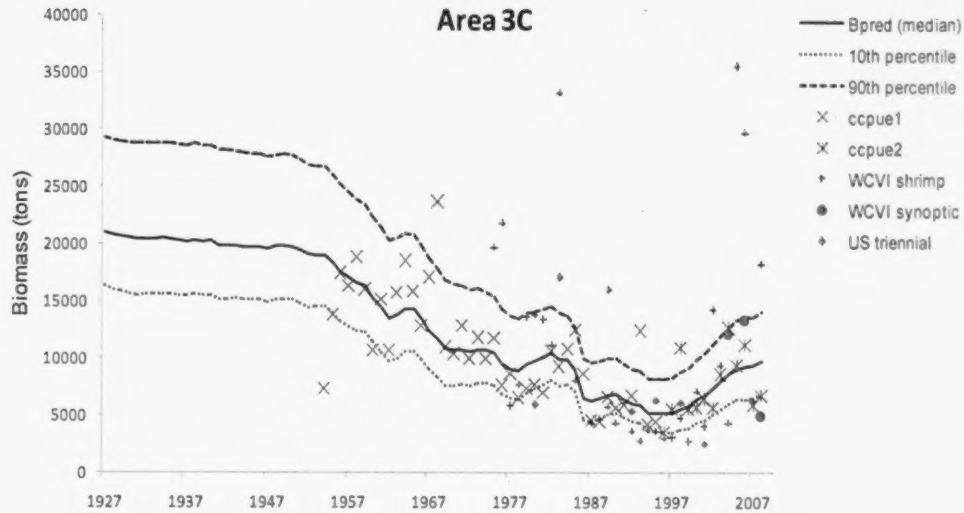


Figure 10: Posterior median and 80% probability interval for stock biomass (t), and the observed stock trend indices divided by their posterior median value for the catchability coefficient for years 1927 to 2009.

Appendix Table 1: Number of lingcod aged in the four areas from 1977 to 2008.

	3C	3D	5AB	5CDE
1977	752	0	443	121
1978	338	0	305	0
1979	871	193	275	0
1980	287	0	0	0
1981	439	0	586	0
1982	783	0	412	0
1983	334	0	576	0
1984	694	0	0	0
1985	216	105	199	0
1986	376	0	200	0
1987	200	0	0	0
1988	165	70	312	0
1989	211	78	210	0
1990	196	0	255	0
1991	175	0	299	0
1992	0	100	150	0
1993	100	0	100	0
1994	50	0	150	96
1995	740	447	100	100
1996	64	0	145	0
1997	150	0	50	103
1998	161	50	0	0
1999	100	50	250	0
2000	0	0	145	50
2001	1	100	100	0
2002	0	50	150	133
2003	69	31	107	128
2004	150	100	200	117
2005	50	100	92	50
2006	246	120	100	0
2007	0	0	50	50
2008	180	0	0	50
Total	**3098**	**1594**	**5961**	**998**

Appendix Table 2: Number of data points used for the growth analysis

	3C	3D	5AB	5CDE	3C	3D	5AB	5CDE
Age	**Female**				**Male**			
1	4	0	4	2	3	0	2	2
2	39	3	30	3	43	2	9	0
3	318	36	160	24	286	10	77	8
4	674	170	462	73	554	55	271	20
5	900	173	648	77	732	59	346	17
6	1017	225	773	90	560	60	323	24
7	836	240	629	104	335	45	211	17
8	516	149	495	112	207	18	108	14
9	298	104	364	101	110	13	77	11
10	175	91	230	81	80	14	38	4
11	110	36	175	61	25	4	35	3
12	92	25	160	56	12	3	18	0
13	41	20	87	33	9	0	8	0
14	31	16	66	15	5	0	7	1
15	12	7	47	16	2	0	4	2
16	10	2	34	11	0	0	0	0
17	5	2	15	4	0	1	0	0
18	5	1	15	6	0	0	0	0
19	2	2	6	5	0	1	0	0
20	0	1	2	1	0	0	0	0
21	1	0	1	0	0	0	0	0
22	2	0	0	0	0	0	0	0
Total	**5088**	**1303**	**4403**	**875**	**2963**	**285**	**1534**	**123**

AREA	Outliers deleted	
3D	Female	(age=7, L=328)
	Male	(age=2, L=481)
		(age=3, L=495)
		(age=4, L=511)
		(age=8, L=900)
		(age=12, L=900)
5AB	Female	(age=5, L=430)
		(age=17, L=910)
		(age=19, L=910)
		(age=16, L=840)
	Male	(age=16, L=1130)
		(age=18, L=1110)
		(age=15, L=1100)
		(age=11, L=1090)
		(age=14, L=1060)
		(age=9, L=1010)

Appendix Table 3: Number of data points used for the maturity analysis

	3C	**3D**	**5AB**	**5CDE**	**3C**	**3D**	**5AB**	**5CDE**
Age	**Female**				**Male**			
1	0	0	4	2	0	0	2	2
2	29	5	30	3	26	0	9	0
3	205	38	128	24	184	0	54	8
4	439	172	358	73	325	0	184	20
5	558	191	519	77	383	0	234	17
6	651	224	600	90	297	0	241	24
7	573	236	488	104	156	0	155	17
8	340	130	378	112	112	0	80	14
9	197	98	282	101	46	0	53	11
10	127	91	177	81	45	0	28	4
11	75	40	134	61	14	0	28	3
12	68	26	122	56	6	0	14	0
13	28	19	64	33	7	0	4	0
14	21	14	55	15	2	0	6	1
15	10	7	33	16	1	0	4	2
16	9	1	28	11	0	0	1	0
17	3	3	11	4	0	0	0	0
18	3	1	14	6	0	0	1	0
19	2	3	6	5	0	0	0	0
20	0	1	2	1	0	0	0	0
21	0	0	1	0	0	0	0	0
22	1	0	0	0	0	0		0
Total	**3339**	**1300**	**3434**	**875**	**1604**	**0**	**1098**	**123**

Appendix Table 4: Number of data points used for the length to weight conversion analysis

	3C	3D	5AB	5CDE	3C	3D	5AB	5CDE
Age	**Female**				**Male**			
1	0	0	0	2	0	0	0	2
2	7	3	3	1	1	1	1	
3	15	12	18	5	13	5	5	4
4	62	41	92	15	54	18	52	8
5	83	66	72	25	75	17	45	9
6	104	77	60	18	33	12	30	2
7	79	65	68	19	29	9	13	1
8	53	44	36	10	16	1	8	4
9	30	28	23	11	3	1	1	2
10	15	13	8	4	4	1	0	1
11	12	8	9	3	3	1	0	0
12	15	6	3	3	1	0	1	0
13	9	3	1	0	2	0	0	0
14	5	0	1	1	2	0	0	0
15	4	0	0	0	1	0	0	0
16	1	0	0	1	0	0	0	0
17	0	0	1	2	0	0	0	0
18	0	0	1	0	0	0	0	0
Total	**494**	**366**	**396**	**120**	**237**	**66**	**156**	**33**

Appendix Table 5: Summary of the priors used for the estimation of the biological parameters and the parameters of the production model.

kb	Prior density function
K (year^{-1})	Normal(0.5,10^2)
L_∞ (mm)	Normal(2000,2000^2)
t_0 (year)	Normal(0,500^2)
σ_g	Uniform(log(0.000001),log(100))
log(*a*)	Normal(0,100^2)
b	Normal(0,100^2)
σ_{ab}	Uniform(log(0.000001),log(10))
Med_age (year)	Uniform(1,20)
σ_{mat}	Uniform(log(0.000001),log(100))
M (year^{-1})	Lognormal(0.193,0.2^2)
h' ($h' \in [0;1]$)	Beta(3.191,661.534)
$h = h'(208 - 0.2) + 0.2$ ($h \in [0.2;208]$)	
SPM Parameters	**Prior density function**
ln(K)	Normal(9.8,1.3)
ln(q_j)	Uniform(-20,200)
p_0	Lognormal(ln(1),0.05)
r (3C)	Normal(0.249,0.087)
r (3D)	Normal(0.250,0.090)
r (5AB)	Normal(0.243,0.090)
r (5CDE)	Normal(0.243,0.095)

Appendix Table 6: Catch series for area 3C in tons. The total catches include the commercial catch (Canada + U.S. + U.S.S.R. + Japan + Poland) and recreational catch which occurred from 1927 to 2008 in area 3C.

	Trawl Catch (t)	Line Catch (t)	Total Commercial Catch (t)	Recreational Catch (t)		Trawl Catch (t)	Line Catch (t)	Total Commercial Catch (t)	Recreational Catch (t)
1927	--	--	245	0	1968	1703	162	1864	7
1928	--	--	259	0	1969	1086	171	1256	7
1929	--	--	186	0	1970	733	286	1019	7
1930	--	--	174	1	1971	988	230	1218	7
1931	--	--	101	1	1972	636	267	903	7
1932	--	--	89	1	1973	882	184	1066	7
1933	--	--	89	1	1974	1069	226	1295	7
1934	--	--	125	1	1975	1655	216	1871	7
1935	--	--	243	1	1976	1208	253	1461	7
1936	--	--	228	2	1977	844	267	1111	7
1937	--	--	35	2	1978	362	200	562	7
1938	--	--	235	2	1979	602	181	783	7
1939	--	--	153	2	1980	623	213	836	7
1940	--	--	553	2	1981	604	240	844	7
1941	--	--	229	2	1982	1510	220	1730	7
1942	--	--	267	3	1983	971	170	1140	7
1943	--	--	354	3	1984	1737	128	1864	5
1944	--	--	286	3	1985	3416	192	3608	10
1945	--	--	285	3	1986	834	268	1102	1
1946	--	--	381	3	1987	492	234	727	16
1947	--	--	107	3	1988	565	118	683	7
1948	--	--	240	4	1989	848	131	979	14
1949	--	--	375	4	1990	1177	238	1415	3
1950	--	--	526	4	1991	1265	181	1446	3
1951	514	212	726	4	1992	976	145	1121	5
1952	259	190	449	4	1993	1428	215	1642	5
1953	269	83	352	4	1994	688	187	875	7
1954	803	241	1044	5	1995	805	198	1003	6
1955	1239	169	1408	5	1996	784	112	896	3
1956	1141	156	1297	5	1997	483	160	643	10
1957	1062	295	1357	5	1998	528	150	677	11
1958	1039	156	1194	5	1999	269	139	408	4
1959	1729	181	1910	5	2000	477	156	633	0
1960	1867	218	2085	6	2001	409	149	558	5
1961	1972	136	2108	6	2002	416	124	541	15
1962	890	228	1118	6	2003	516	158	674	3
1963	646	180	825	6	2004	635	145	780	3
1964	1183	101	1284	6	2005	773	151	924	4
1965	1889	122	2011	6	2006	821	48	870	6
1966	2071	158	2229	7	2007	625	78	703	15
1967	1796	246	2042	7	2008	691	115	806	19

Appendix Table 7: Catch series for area 3D in tons. The total catches include the commercial catch (Canada + U.S. + U.S.S.R. + Japan + Poland) and recreational catch which occurred from 1927 to 2008 in area 3D.

	Trawl Catch (t)	Line Catch (t)	Total Commercial Catch (t)	Recreational Catch (t)		Trawl Catch (t)	Line Catch (t)	Total Commercial Catch (t)	Recreational Catch (t)
1927	--	--	44	0	1968	880	108	988	6
1928	--	--	64	0	1969	622	78	700	6
1929	--	--	13	0	1970	461	159	619	6
1930	--	--	36	0	1971	268	115	383	6
1931	--	--	4	1	1972	94	182	276	6
1932	--	--	0	1	1973	175	84	260	6
1933	--	--	0	1	1974	273	113	386	6
1934	--	--	0	1	1975	354	90	445	6
1935	--	--	3	1	1976	246	91	336	6
1936	--	--	7	1	1977	158	108	265	6
1937	--	--	4	1	1978	196	88	284	6
1938	--	--	1	2	1979	147	101	248	6
1939	--	--	3	2	1980	127	88	214	6
1940	--	--	6	2	1981	87	113	200	6
1941	--	--	6	2	1982	49	175	223	6
1942	--	--	8	2	1983	447	153	600	6
1943	--	--	620	2	1984	322	153	475	6
1944	--	--	164	2	1985	380	194	574	6
1945	--	--	287	3	1986	246	229	475	6
1946	--	--	175	3	1987	88	327	415	6
1947	--	--	53	3	1988	283	242	525	6
1948	--	--	24	3	1989	300	196	495	6
1949	--	--	73	3	1990	421	241	661	6
1950	--	--	88	3	1991	549	284	833	6
1951	73	168	240	3	1992	554	310	864	6
1952	61	185	246	4	1993	448	673	1122	6
1953	34	89	123	4	1994	847	552	1400	6
1954	60	140	199	4	1995	502	373	874	6
1955	156	93	249	4	1996	222	186	409	6
1956	167	125	292	4	1997	97	173	269	6
1957	129	135	264	4	1998	162	186	348	1
1958	108	120	228	5	1999	127	197	323	2
1959	64	94	158	5	2000	277	220	497	0
1960	87	106	193	5	2001	187	167	354	7
1961	200	116	315	5	2002	183	220	402	12
1962	286	104	390	5	2003	227	178	405	3
1963	115	122	238	5	2004	230	194	424	3
1964	226	85	311	5	2005	214	166	380	4
1965	505	90	596	6	2006	168	125	293	8
1966	607	136	743	6	2007	259	156	415	10
1967	474	167	641	6	2008	97	138	235	17

Appendix Table 8: Catch series for area 5AB in tons. The total catches include the commercial catch (Canada + U.S. + U.S.S.R. + Japan) and recreational catch which occurred from 1927 to 2008 in area 5AB.

	Trawl Catch (t)	Line Catch (t)	Total Commercial Catch (t)	Recreational Catch (t)		Trawl Catch (t)	Line Catch (t)	Total Commercial Catch (t)	Recreational Catch (t)
1927	--	--	0	0	1968	2302	41	2343	3
1928	--	--	0	0	1969	1157	57	1214	4
1929	--	--	0	0	1970	990	82	1073	4
1930	--	--	1	0	1971	656	58	714	4
1931	--	--	0	0	1972	649	109	758	4
1932	--	--	0	0	1973	600	67	666	4
1933	--	--	0	1	1974	916	84	1000	4
1934	--	--	0	1	1975	553	75	628	4
1935	--	--	3	1	1976	613	92	705	4
1936	--	--	1	1	1977	381	78	460	4
1937	--	--	1	1	1978	288	39	327	4
1938	--	--	1	1	1979	342	54	396	4
1939	--	--	3	1	1980	413	58	471	4
1940	--	--	7	1	1981	730	49	779	4
1941	--	--	39	1	1982	1047	54	1101	4
1942	--	--	54	1	1983	1345	57	1402	4
1943	--	--	86	1	1984	716	75	790	4
1944	--	--	153	1	1985	877	85	962	4
1945	--	--	256	2	1986	1651	61	1713	4
1946	--	--	231	2	1987	1431	131	1562	4
1947	--	--	16	2	1988	1291	125	1415	4
1948	--	--	47	2	1989	1616	159	1775	4
1949	--	--	95	2	1990	2119	200	2319	4
1950	--	--	46	2	1991	1857	305	2162	4
1951	80	35	115	2	1992	1262	262	1524	4
1952	71	32	103	2	1993	1421	102	1524	1
1953	17	4	21	2	1994	1334	129	1462	1
1954	217	10	227	2	1995	1239	166	1406	2
1955	265	19	284	2	1996	659	187	846	2
1956	595	35	630	2	1997	411	143	555	4
1957	598	12	610	3	1998	454	216	670	4
1958	568	2	569	3	1999	583	200	783	3
1959	616	4	620	3	2000	919	189	1108	4
1960	658	23	680	3	2001	641	206	847	4
1961	711	49	760	3	2002	892	190	1082	4
1962	938	69	1007	3	2003	807	156	963	4
1963	642	77	719	3	2004	706	188	894	4
1964	687	33	720	3	2005	567	199	766	4
1965	919	23	942	3	2006	750	148	898	6
1966	1604	59	1664	3	2007	549	211	760	7
1967	1714	40	1754	3	2008	398	370	768	4

Appendix Table 9: Catch series for area 5CDE in tons. The total catches include the commercial catch (Canada + U.S. + U.S.S.R. + Japan) and recreational catch which occurred from 1927 to 2008 in area 5CDE.

	Trawl Catch (t)	Line Catch (t)	Total Commercial Catch (t)	Recreational Catch (t)		Trawl Catch (t)	Line Catch (t)	Total Commercial Catch (t)	Recreational Catch (t)
1927	--	--	13	0	1968	418	69	487	8
1928	--	--	26	0	1969	258	105	363	8
1929	--	--	35	0	1970	216	130	346	9
1930	--	--	17	1	1971	333	152	485	9
1931	--	--	1	1	1972	167	139	306	9
1932	--	--	3	1	1973	132	102	235	9
1933	--	--	4	1	1974	130	131	260	9
1934	--	--	1	1	1975	179	121	300	9
1935	--	--	6	2	1976	113	87	200	9
1936	--	--	6	2	1977	132	68	200	9
1937	--	--	6	2	1978	52	63	114	9
1938	--	--	7	2	1979	129	76	205	9
1939	--	--	8	2	1980	174	108	283	9
1940	--	--	7	3	1981	267	71	338	9
1941	--	--	8	3	1982	194	109	302	9
1942	--	--	22	3	1983	145	121	266	9
1943	--	--	72	3	1984	154	173	327	9
1944	--	--	117	3	1985	153	204	357	9
1945	--	--	179	4	1986	149	226	375	9
1946	--	--	492	4	1987	372	378	751	9
1947	--	--	9	4	1988	369	369	738	9
1948	--	--	115	4	1989	292	359	650	9
1949	--	--	182	4	1990	332	444	776	9
1950	--	--	94	5	1991	539	375	914	9
1951	136	67	203	5	1992	454	395	849	4
1952	62	49	111	5	1993	466	456	922	5
1953	22	6	28	5	1994	558	341	899	5
1954	100	10	110	5	1995	563	347	910	7
1955	216	4	220	6	1996	213	218	430	7
1956	92	5	97	6	1997	125	143	268	6
1957	128	9	137	6	1998	91	257	349	6
1958	74	9	83	6	1999	93	444	537	8
1959	116	18	134	6	2000	178	439	617	11
1960	116	23	139	7	2001	135	403	538	15
1961	96	36	132	7	2002	322	278	600	14
1962	113	58	171	7	2003	194	370	563	8
1963	146	51	198	7	2004	203	406	609	11
1964	215	48	263	7	2005	140	396	536	8
1965	293	74	366	8	2006	92	270	361	10
1966	324	54	378	8	2007	110	380	490	2
1967	345	68	414	8	2008	106	425	531	21

Appendix Table 10: Summary of the abundance index series used for the stock assessment in the four areas.

Area	Series *j*	Time period	Source	Comment
3C	*com*	1954 to 2006	Commercial trawl data	25% Qualified CPUE in kg/h
	tri	1980 to 2001 but 1986	NMFS trawl surveys	Triennial CPUE in tonnes
	sh	1975 to 2008 but 1984 and 1986	DFO trawl surveys: West Coast Vancouver Island Shrimp Survey	relative biomass in tonnes
	sy	2004 - 2006 - 2008	DFO trawl surveys: West Coast Vancouver Island Synoptic Survey	relative biomass in tonnes
3D	*com*	1954 to 2006	Commercial trawl data	25% Qualified CPUE in kg/h
	sh	1975 to 2008 but 1984 and 1986	DFO trawl surveys: West Coast Vancouver Island Shrimp Survey	relative biomass in tonnes
	sy	2004 - 2006 - 2008	DFO trawl surveys: West Coast Vancouver Island Synoptic Survey	relative biomass in tonnes
5AB	*com*	1954 to 2006	Commercial trawl data	25% Qualified CPUE in kg/h
	sh	1999 to 2008	DFO trawl surveys: Queen Charlotte Sound Shrimp Survey	relative biomass in kg
	sy	2003 - 2004 - 2005 - 2007	DFO trawl surveys: Queen Charlotte Sound Synoptic Survey	relative biomass in kg
5CDE	*com*	1954 to 2006	Commercial trawl data	25% Qualified CPUE in kg/h
	sy	2005 - 2007	DFO trawl surveys: Hecate Strait Synoptic Survey	relative biomass in kg
	multi	1984 - 1987 - 1989 - 1991 - 1993 - 1995 - 1996 - 1998 - 2000 - 2002 - 2003	DFO trawl surveys: Hecate Strait Multispecies Assemblage Survey	kg/h

Appendix Table 11: Relative stock trend indices for B.C. lingcod in area 3C. 'NA' indicates no index available for that year.

	Qualified CPUE (kg/h)	US Triennal Survey (t)	WCVI Shrimp Survey (t)	WCVI Synoptic Survey (t)		Qualified CPUE (kg/h)	US Triennal Survey (t)	WCVI Shrimp Survey (t)	WCVI Synoptic Survey (t)
1927	NA	NA	NA	NA	1968	603	NA	NA	NA
1928	NA	NA	NA	NA	1969	289	NA	NA	NA
1929	NA	NA	NA	NA	1970	282	NA	NA	NA
1930	NA	NA	NA	NA	1971	358	NA	NA	NA
1931	NA	NA	NA	NA	1972	286	NA	NA	NA
1932	NA	NA	NA	NA	1973	351	NA	NA	NA
1933	NA	NA	NA	NA	1974	303	NA	NA	NA
1934	NA	NA	NA	NA	1975	370	NA	1372	NA
1935	NA	NA	NA	NA	1976	248	NA	1519	NA
1936	NA	NA	NA	NA	1977	288	NA	409	NA
1937	NA	NA	NA	NA	1978	226	NA	534	NA
1938	NA	NA	NA	NA	1979	260	NA	951	NA
1939	NA	NA	NA	NA	1980	283	3125	962	NA
1940	NA	NA	NA	NA	1981	262	NA	934	NA
1941	NA	NA	NA	NA	1982	412	NA	778	NA
1942	NA	NA	NA	NA	1983	372	8956	2312	NA
1943	NA	NA	NA	NA	1984	445	NA	NA	NA
1944	NA	NA	NA	NA	1985	531	NA	563	NA
1945	NA	NA	NA	NA	1986	380	NA	NA	NA
1946	NA	NA	NA	NA	1987	206	NA	301	NA
1947	NA	NA	NA	NA	1988	208	NA	331	NA
1948	NA	NA	NA	NA	1989	316	8436	401	NA
1949	NA	NA	NA	NA	1990	278	NA	305	NA
1950	NA	NA	NA	NA	1991	302	NA	429	NA
1951	NA	NA	NA	NA	1992	354	2821	253	NA
1952	NA	NA	NA	NA	1993	671	NA	193	NA
1953	NA	NA	NA	NA	1994	237	NA	262	NA
1954	123	NA	NA	NA	1995	257	3335	252	NA
1955	237	NA	NA	NA	1996	148	NA	213	NA
1956	310	NA	NA	NA	1997	239	NA	216	NA
1957	298	NA	NA	NA	1998	483	3207	333	NA
1958	356	NA	NA	NA	1999	255	NA	190	NA
1959	312	NA	NA	NA	2000	270	NA	494	NA
1960	214	NA	NA	NA	2001	312	1326	282	NA
1961	312	NA	NA	NA	2002	284	NA	993	NA
1962	227	NA	NA	NA	2003	443	NA	656	NA
1963	345	NA	NA	NA	2004	673	NA	303	1740
1964	419	NA	NA	NA	2005	514	NA	2477	NA
1965	368	NA	NA	NA	2006	629	NA	2070	1922
1966	308	NA	NA	NA	2007	344	NA	431	NA
1967	423	NA	NA	NA	2008	402	NA	1268	712

Appendix Table 12: Relative stock trend indices for B.C. lingcod in area 3D. 'NA' indicates no index available for that year.

	Qualified CPUE (kg/h)	WCVI Shrimp Survey (t)	WCVI Synoptic Survey (t)		Qualified CPUE (kg/h)	WCVI Shrimp Survey (t)	WCVI Synoptic Survey (t)
1927	NA	NA	NA	1968	543	NA	NA
1928	NA	NA	NA	1969	295	NA	NA
1929	NA	NA	NA	1970	272	NA	NA
1930	NA	NA	NA	1971	205	NA	NA
1931	NA	NA	NA	1972	190	NA	NA
1932	NA	NA	NA	1973	393	NA	NA
1933	NA	NA	NA	1974	541	NA	NA
1934	NA	NA	NA	1975	284	181	NA
1935	NA	NA	NA	1976	313	505	NA
1936	NA	NA	NA	1977	305	298	NA
1937	NA	NA	NA	1978	477	641	NA
1938	NA	NA	NA	1979	314	398	NA
1939	NA	NA	NA	1980	215	501	NA
1940	NA	NA	NA	1981	218	443	NA
1941	NA	NA	NA	1982	191	405	NA
1942	NA	NA	NA	1983	337	1026	NA
1943	NA	NA	NA	1984	282	NA	NA
1944	NA	NA	NA	1985	498	108	NA
1945	NA	NA	NA	1986	316	NA	NA
1946	NA	NA	NA	1987	309	69	NA
1947	NA	NA	NA	1988	316	321	NA
1948	NA	NA	NA	1989	280	56	NA
1949	NA	NA	NA	1990	370	485	NA
1950	NA	NA	NA	1991	304	136	NA
1951	NA	NA	NA	1992	252	1001	NA
1952	NA	NA	NA	1993	192	546	NA
1953	NA	NA	NA	1994	299	290	NA
1954	179	NA	NA	1995	194	507	NA
1955	210	NA	NA	1996	210	252	NA
1956	315	NA	NA	1997	278	316	NA
1957	275	NA	NA	1998	363	622	NA
1958	182	NA	NA	1999	308	1153	NA
1959	402	NA	NA	2000	872	885	NA
1960	486	NA	NA	2001	351	368	NA
1961	307	NA	NA	2002	406	4313	NA
1962	181	NA	NA	2003	472	775	NA
1963	258	NA	NA	2004	613	413	5421
1964	366	NA	NA	2005	577	233	NA
1965	287	NA	NA	2006	363	186	2150
1966	439	NA	NA	2007	323	36	NA
1967	395	NA	NA	2008	209	30	780

Appendix Table 13: Relative stock trend indices for B.C. lingcod in area 5AB. 'NA' indicates no index available for that year.

	Qualified CPUE (kg/h)	QCS Shrimp Survey (kg)	QCS Synoptic Survey (kg)		Qualified CPUE (kg/h)	QCS Shrimp Survey (kg)	QCS Synoptic Survey (kg)
1927	NA	NA	NA	1968	283	NA	NA
1928	NA	NA	NA	1969	141	NA	NA
1929	NA	NA	NA	1970	220	NA	NA
1930	NA	NA	NA	1971	138	NA	NA
1931	NA	NA	NA	1972	194	NA	NA
1932	NA	NA	NA	1973	162	NA	NA
1933	NA	NA	NA	1974	262	NA	NA
1934	NA	NA	NA	1975	185	NA	NA
1935	NA	NA	NA	1976	249	NA	NA
1936	NA	NA	NA	1977	191	NA	NA
1937	NA	NA	NA	1978	218	NA	NA
1938	NA	NA	NA	1979	222	NA	NA
1939	NA	NA	NA	1980	213	NA	NA
1940	NA	NA	NA	1981	270	NA	NA
1941	NA	NA	NA	1982	267	NA	NA
1942	NA	NA	NA	1983	327	NA	NA
1943	NA	NA	NA	1984	212	NA	NA
1944	NA	NA	NA	1985	280	NA	NA
1945	NA	NA	NA	1986	433	NA	NA
1946	NA	NA	NA	1987	292	NA	NA
1947	NA	NA	NA	1988	311	NA	NA
1948	NA	NA	NA	1989	318	NA	NA
1949	NA	NA	NA	1990	293	NA	NA
1950	NA	NA	NA	1991	326	NA	NA
1951	NA	NA	NA	1992	244	NA	NA
1952	NA	NA	NA	1993	266	NA	NA
1953	NA	NA	NA	1994	244	NA	NA
1954	514	NA	NA	1995	185	NA	NA
1955	140	NA	NA	1996	206	NA	NA
1956	296	NA	NA	1997	217	NA	NA
1957	247	NA	NA	1998	206	NA	NA
1958	204	NA	NA	1999	185	NA	69276
1959	312	NA	NA	2000	297	NA	60488
1960	251	NA	NA	2001	240	NA	55842
1961	325	NA	NA	2002	228	NA	41475
1962	252	NA	NA	2003	224	742442	23341
1963	204	NA	NA	2004	281	776814	51196
1964	253	NA	NA	2005	276	546882	41564
1965	221	NA	NA	2006	268	NA	30920
1966	297	NA	NA	2007	328	587512	27940
1967	313	NA	NA	2008	352	NA	50321

Appendix Table 14: Relative stock trend indices for B.C. lingcod in area 5CDE. 'NA' indicates no index available for that year.

	Qualified CPUE (kg/h)	HS Synotpic Survey (kg)	HS Multi species Survey (kg/h)		Qualified CPUE (kg/h)	HS Synotpic Survey (kg)	HS Multi species Survey (kg/h)
1927	NA	NA	NA	1968	253	NA	NA
1928	NA	NA	NA	1969	157	NA	NA
1929	NA	NA	NA	1970	196	NA	NA
1930	NA	NA	NA	1971	271	NA	NA
1931	NA	NA	NA	1972	398	NA	NA
1932	NA	NA	NA	1973	359	NA	NA
1933	NA	NA	NA	1974	76	NA	NA
1934	NA	NA	NA	1975	611	NA	NA
1935	NA	NA	NA	1976	281	NA	NA
1936	NA	NA	NA	1977	192	NA	NA
1937	NA	NA	NA	1978	18	NA	NA
1938	NA	NA	NA	1979	232	NA	NA
1939	NA	NA	NA	1980	109	NA	NA
1940	NA	NA	NA	1981	223	NA	NA
1941	NA	NA	NA	1982	268	NA	NA
1942	NA	NA	NA	1983	203	NA	NA
1943	NA	NA	NA	1984	113	NA	73
1944	NA	NA	NA	1985	252	NA	NA
1945	NA	NA	NA	1986	236	NA	NA
1946	NA	NA	NA	1987	413	NA	71
1947	NA	NA	NA	1988	348	NA	NA
1948	NA	NA	NA	1989	315	NA	155
1949	NA	NA	NA	1990	297	NA	NA
1950	NA	NA	NA	1991	397	NA	81
1951	NA	NA	NA	1992	330	NA	NA
1952	NA	NA	NA	1993	327	NA	44
1953	NA	NA	NA	1994	476	NA	NA
1954	616	NA	NA	1995	320	NA	31
1955	856	NA	NA	1996	266	NA	34
1956	221	NA	NA	1997	164	NA	NA
1957	872	NA	NA	1998	135	NA	58
1958	124	NA	NA	1999	249	NA	NA
1959	81	NA	NA	2000	265	NA	36
1960	141	NA	NA	2001	208	NA	NA
1961	107	NA	NA	2002	326	NA	60
1962	170	NA	NA	2003	302	NA	37
1963	344	NA	NA	2004	266	NA	NA
1964	455	NA	NA	2005	607	205097	NA
1965	892	NA	NA	2006	316	NA	NA
1966	399	NA	NA	2007	265	267076	NA
1967	347	NA	NA	2008	349	NA	NA

Appendix Table 15: Posterior mean, SD, CV, 10^{th}, 50^{th} and 90^{th} percentiles for key parameters and stock status indicators for B.C. offshore lingcod in area 3D, 5AB and 5CDE.

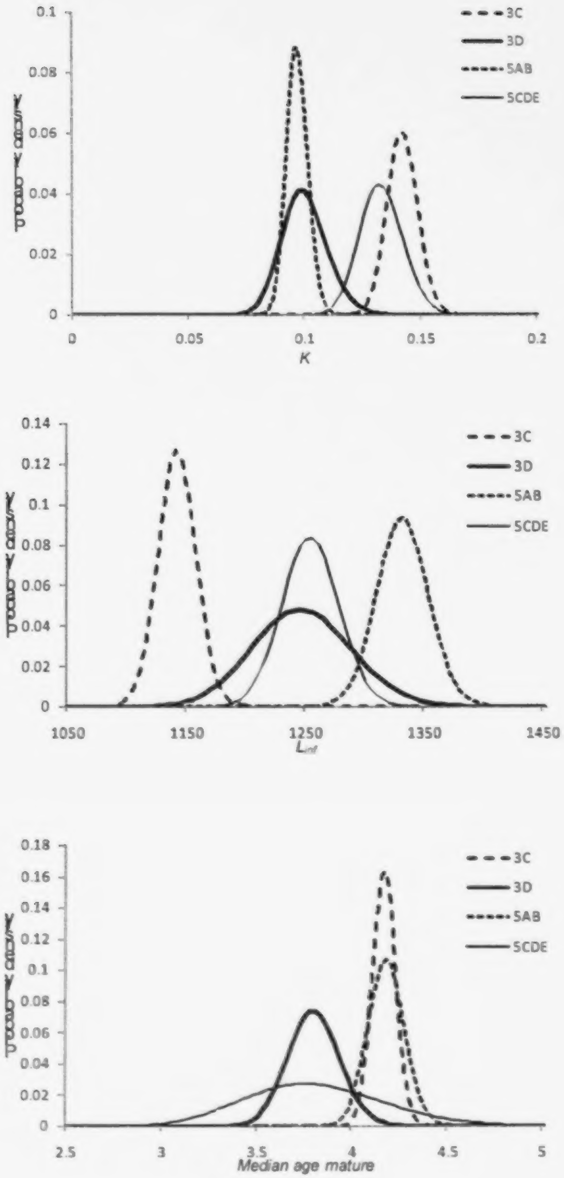
Area 3D	**Mean**	**SD**	**CV**	**10th**	**Median**	**90th**
K	**48310**	66050	1.367	12010	27330	104100
r	**0.274**	0.084	0.307	0.166	0.274	0.383
MSY	**3175**	4599	1.449	793	1758	6861
B_{2009}	**45320**	64650	1.427	9877	24840	99580
B_{1927}	**48370**	66420	1.373	11990	27430	104300
B_{2009}/B_{1927}	**0.902**	0.112	0.124	0.763	0.908	1.037
C_{2009}/MSY	**0.165**	0.118	0.713	0.037	0.144	0.318
F_{2009}/F_{MSY}	**0.099**	0.089	0.905	0.019	0.078	0.196
B_{2009}/B_{MSY}	**1.802**	0.202	0.112	1.547	1.820	2.038
C_{2009}/RepY$_{2009}$	**3.650E+05**	8.878E+05	2.432	0.177	0.497	2.524E+06
B_{MSY}	**24150**	33020	1.367	6004	13670	52040
RepY$_{2009}$	**734**	1223	1.666	0	508	1426
q_com1	**1.35E-02**	0.0101	0.744	2.78E-03	1.12E-02	2.79E-02
q_com2	**1.77E-02**	0.0144	0.815	3.36E-03	1.39E-02	3.71E-02
q_sh	**1.69E-02**	0.0137	0.813	3.28E-03	1.33E-02	3.50E-02
q_sy	**1.21E-01**	0.1339	1.107	1.70E-02	7.75E-02	2.76E-01
p(B_{2009}>B_{MSY})	**9.98E-01**	--	--	--	--	--
p(C_{2009}>RepY$_{2009}$)	**0.244**	--	--	--	--	--

Area 5AB	Mean	SD	CV	10th	Median	90th
K	**31440**	27970	0.890	16970	24660	48760
r	**0.238**	0.069	0.291	0.150	0.236	0.328
MSY	**1752**	1709	0.975	1064	1399	2511
B_{2009}	**25680**	28270	1.101	11060	18810	43330
B_{1927}	**31490**	27880	0.885	16830	24660	49160
B_{2009}/B_{1927}	**0.774**	0.148	0.191	0.576	0.781	0.957
C_{2009}/MSY	**0.536**	0.169	0.316	0.308	0.552	0.726
F_{2009}/F_{MSY}	**0.379**	0.191	0.504	0.164	0.353	0.617
B_{2009}/B_{MSY}	**1.545**	0.285	0.185	1.160	1.565	1.895
C_{2009}/RepY$_{2009}$	**3.209E+05**	1.542E+06	4.805	0.638	0.812	1.878E+00
B_{MSY}	**15720**	13980	0.889	8483	12330	24380
RepY$_{2009}$	**899**	468	0.520	412	951	1212
q_com1	**9.49E-03**	0.0040	0.419	4.26E-03	9.41E-03	1.47E-02
q_com2	**8.17E-03**	0.0042	0.513	3.21E-03	7.70E-03	1.36E-02
q_sh	**2.93E+00**	2.2070	0.752	8.58E-01	2.37E+00	5.65E+00
q_sy	**4.03E+01**	21.4600	0.533	1.55E+01	3.74E+01	6.78E+01
p(B_{2009}>B_{MSY})	**9.61E-01**	--	--	--	--	--
p(C_{2009}>RepY$_{2009}$)	**0.277**	--	--	--	--	--

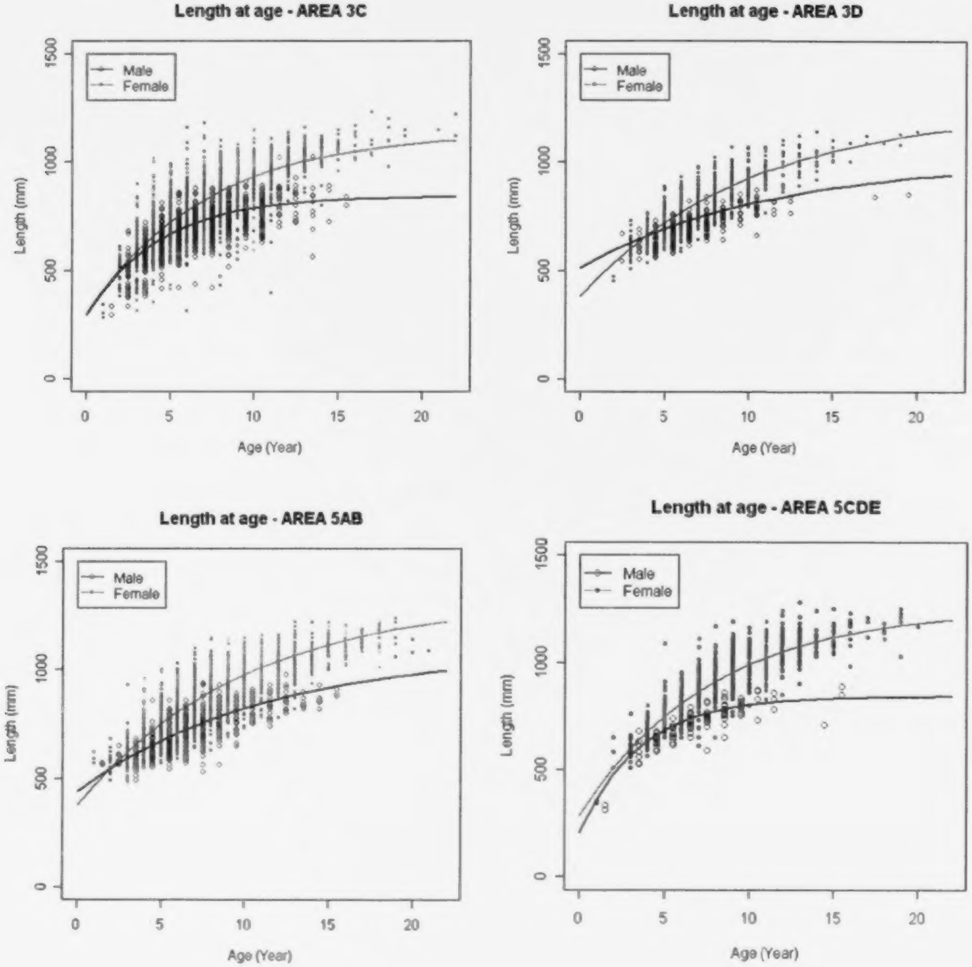
Area 5CDE	Mean	SD	CV	10th	Median	90th
K	**28220**	51420	1.822	8014	14410	57620
r	**0.245**	0.083	0.339	0.140	0.244	0.354
MSY	**1589**	2991	1.882	534	780.8	3102
B_{2009}	**24910**	51300	2.059	4605	10700	55580
B_{1927}	**28230**	51710	1.832	7964	14370	57550
B_{2009}/B_{1927}	**0.766**	0.180	0.235	0.520	0.773	0.997
C_{2009}/MSY	**0.661**	0.336	0.508	0.178	0.708	1.035
F_{2009}/F_{MSY}	**0.509**	0.373	0.732	0.091	0.455	0.978
B_{2009}/B_{MSY}	**1.530**	0.351	0.229	1.048	1.550	1.974
C_{2009}/RepY$_{2009}$	**4.594E+05**	1.526E+06	3.322	0.718	1.045	5.661E+00
B_{MSY}	**14110**	25710	1.822	4007	7203	28810
RepY$_{2009}$	**555**	689	1.241	98	529	769
q_com1	**1.56E-02**	0.0097	0.621	3.39E-03	1.47E-02	2.89E-02
q_com2	**1.60E-02**	0.0119	0.747	2.65E-03	1.37E-02	3.28E-02
q_multi	**5.83E-03**	0.0041	0.702	1.04E-03	5.16E-03	1.16E-02
q_sy	**2.59E+01**	19.7500	0.761	4.28E+00	2.21E+01	5.32E+01
p(B_{2009}>B_{MSY})	**9.19E-01**	--	--	--	--	--
p(C_{2009}>RepY$_{2009}$)	**0.579**	--	--	--	--	--

Appendix Table 16: Total Allowable Catch (TAC), in tons, implemented in the four areas for the commercial fishery since 1987.

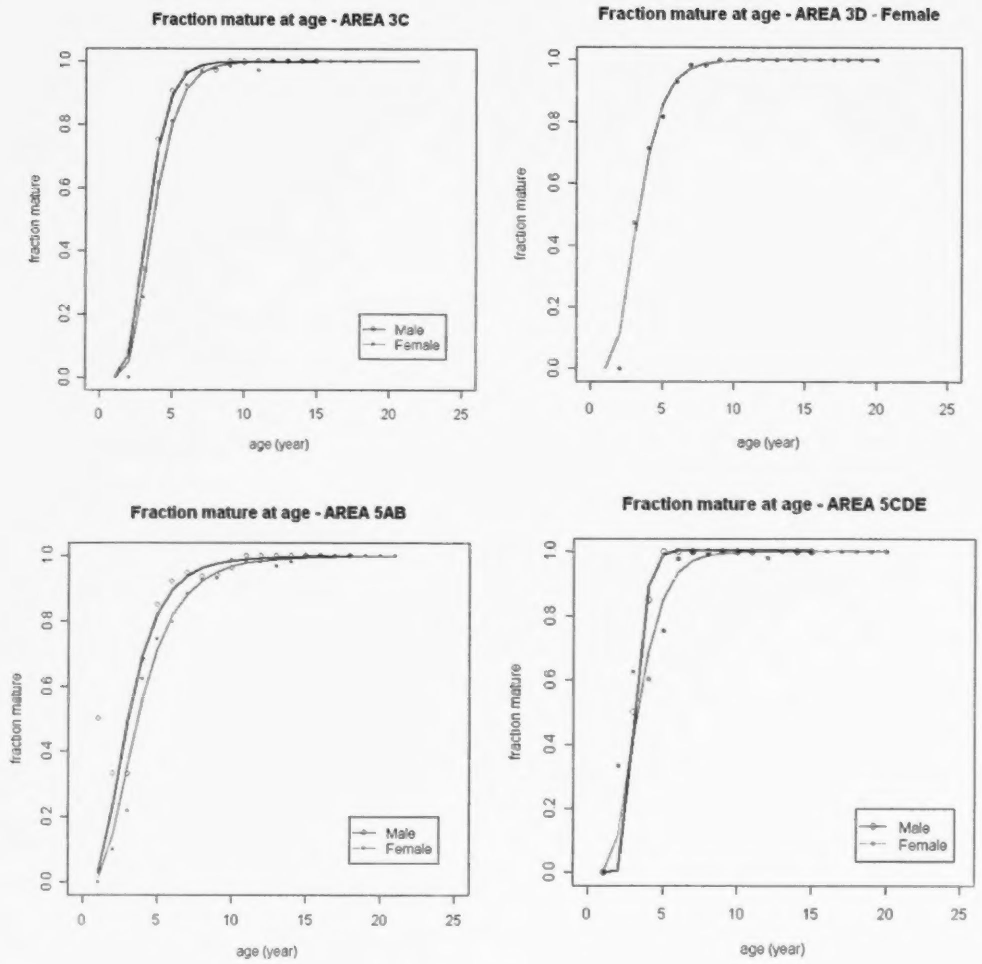
	3C	3D	5AB	5CDE
1987	1400	--	--	--
1988	1400	--	--	--
1989	1400	--	--	--
1990	1400	--	--	--
1991	2000	--	--	--
1992	2000	--	--	--
1993	2000	600	1650	1000
1994	2000	600	1650	1000
1995	2100	600	1650	1000
1996	1540	660	1815	1100
1997	1400	400	1100	1000
1998	950	400	1100	1000
1999	950	400	1062	1000
2000	950	400	1062	1000
2001	950	400	1062	1000
2002	950	400	1062	1000
2003	950	400	1062	1000
2004	950	400	1062	1000
2005	950	400	1062	1000
2006	950	400	1062	1000
2007	950	400	1062	1000
2008	950	400	1062	1000



Appendix Figure 1: Plots of the lognormal approximations of the posterior distributions of the carrying capacity (K), the maximum length (L_{inf}), and the median age mature for the female lingcod in the four areas.

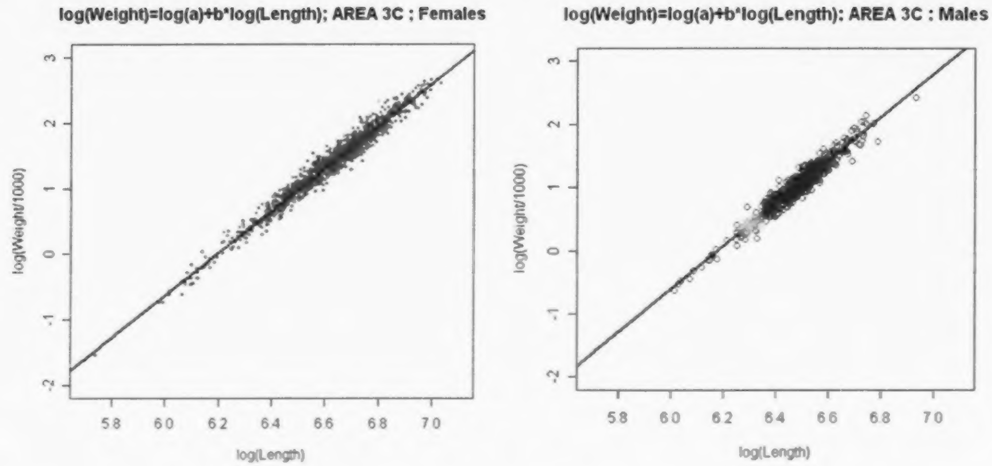


Appendix Figure 2: Plots of the observed length at age for both female (red) and male (blue) and the von Bertalanffy curves fitted to the data for the four areas.

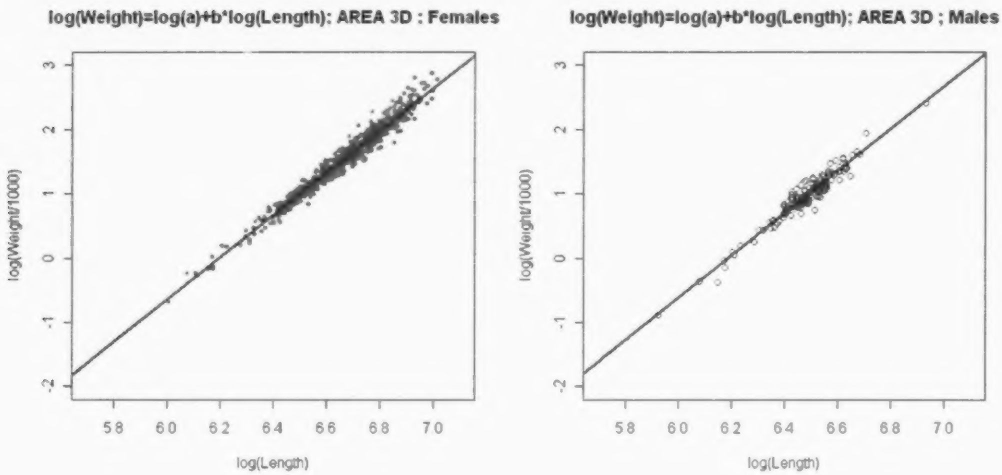


Appendix Figure 3: Plots of the observed fraction mature at age for both female (red) and male (blue) and the cumulative lognormal curves fitted to the data for the four areas

Area 3C

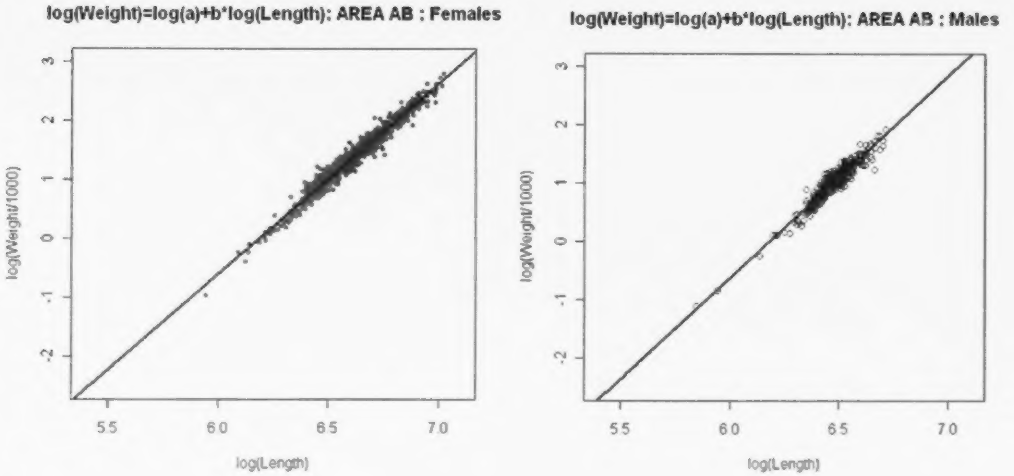


Area 3D

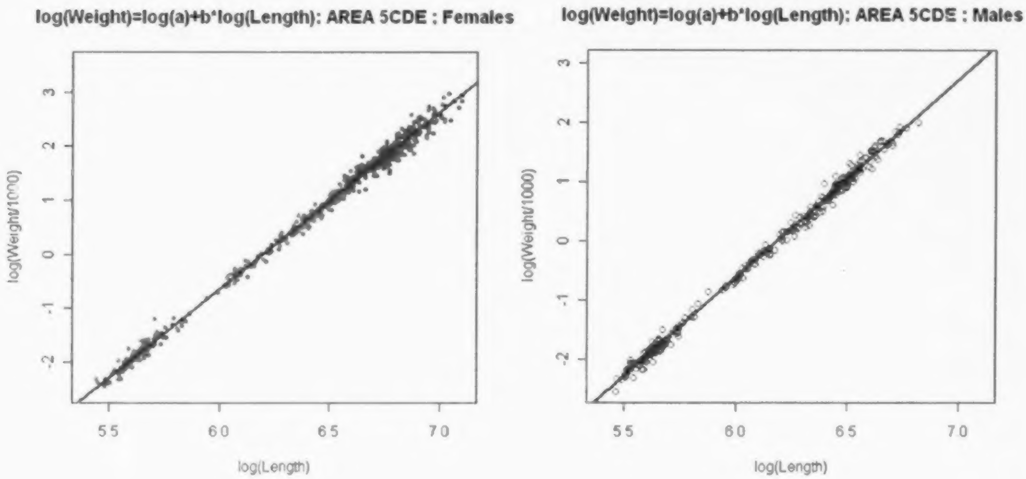


Appendix Figure 4: Plots of the observed length and weight at age (without outliers) for both female (red, on the left) and male (blue, on the right) and the curves (log(Wt) = log(a) + b*log(Lt)) fitted to the data for the four areas.

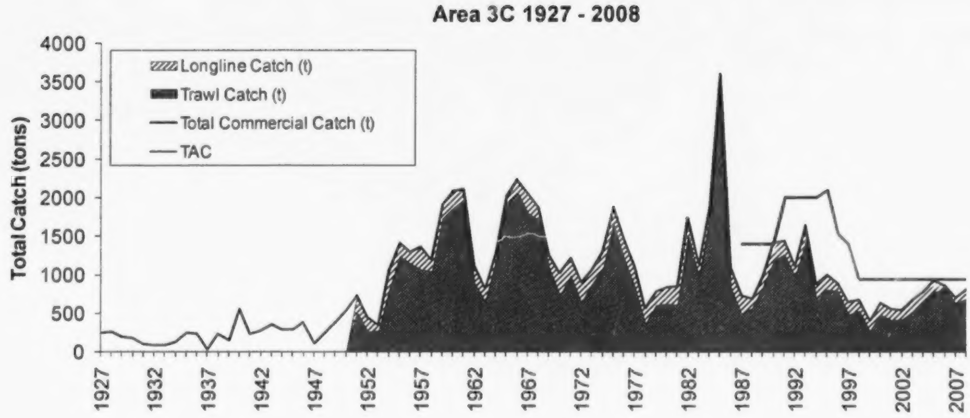
Area 5AB

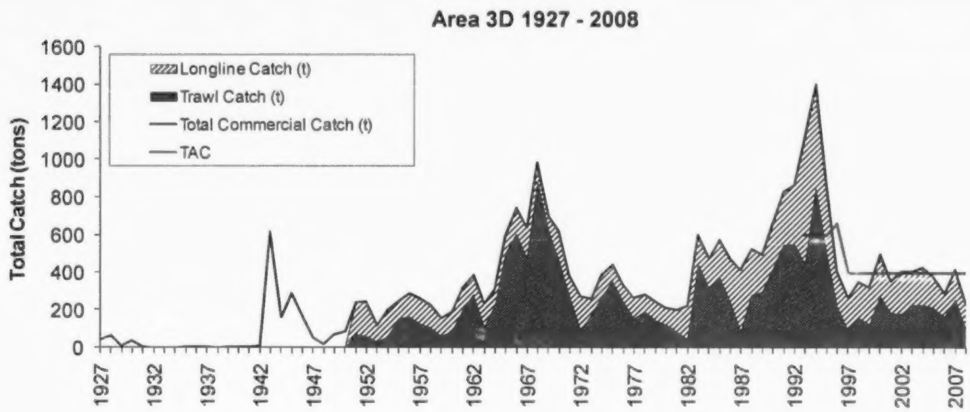


Area 5CDE

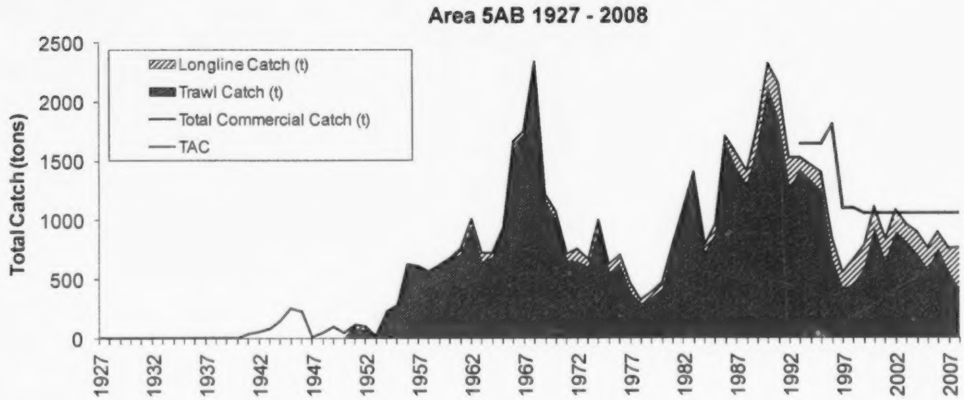


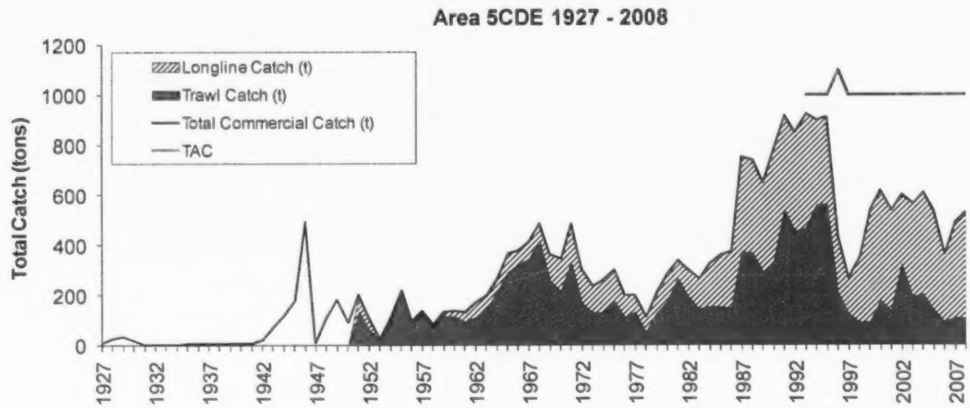
Appendix Figure 4 continued.



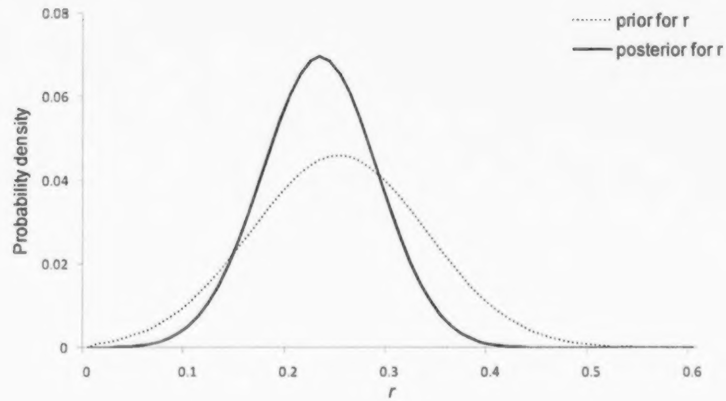


Appendix Figure 5: Plot of the commercial catch series and the TAC for the four areas from 1927 to 2008. The total commercial catches include the longline fishery catches (Canada) and the trawl fishery catches (Canada + U.S. + U.S.S.R. + Japan + Poland).

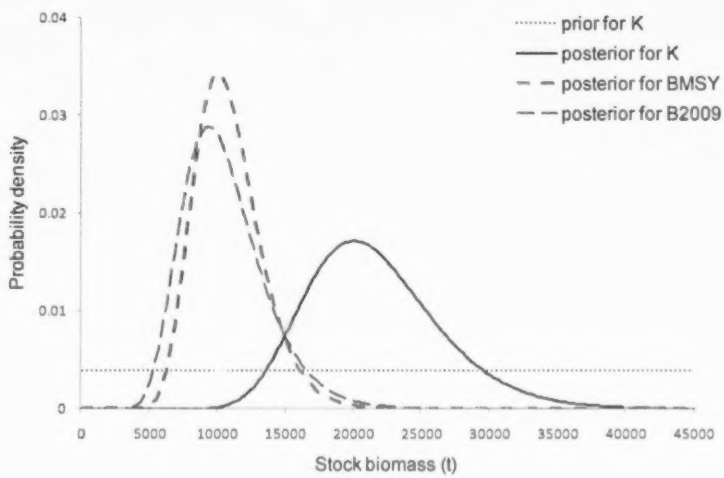




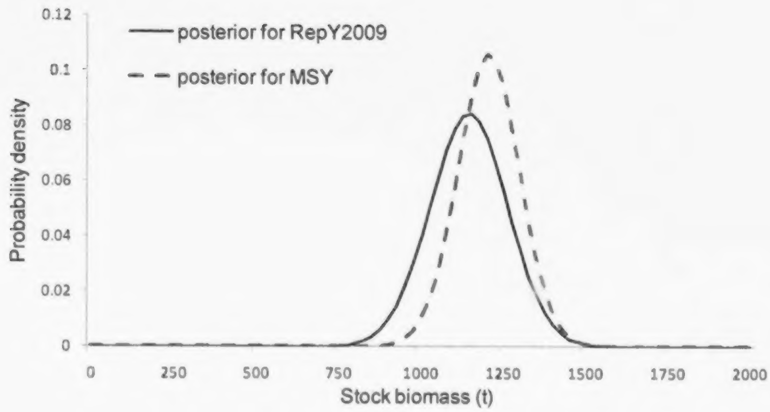
Appendix Figure 5 continued.



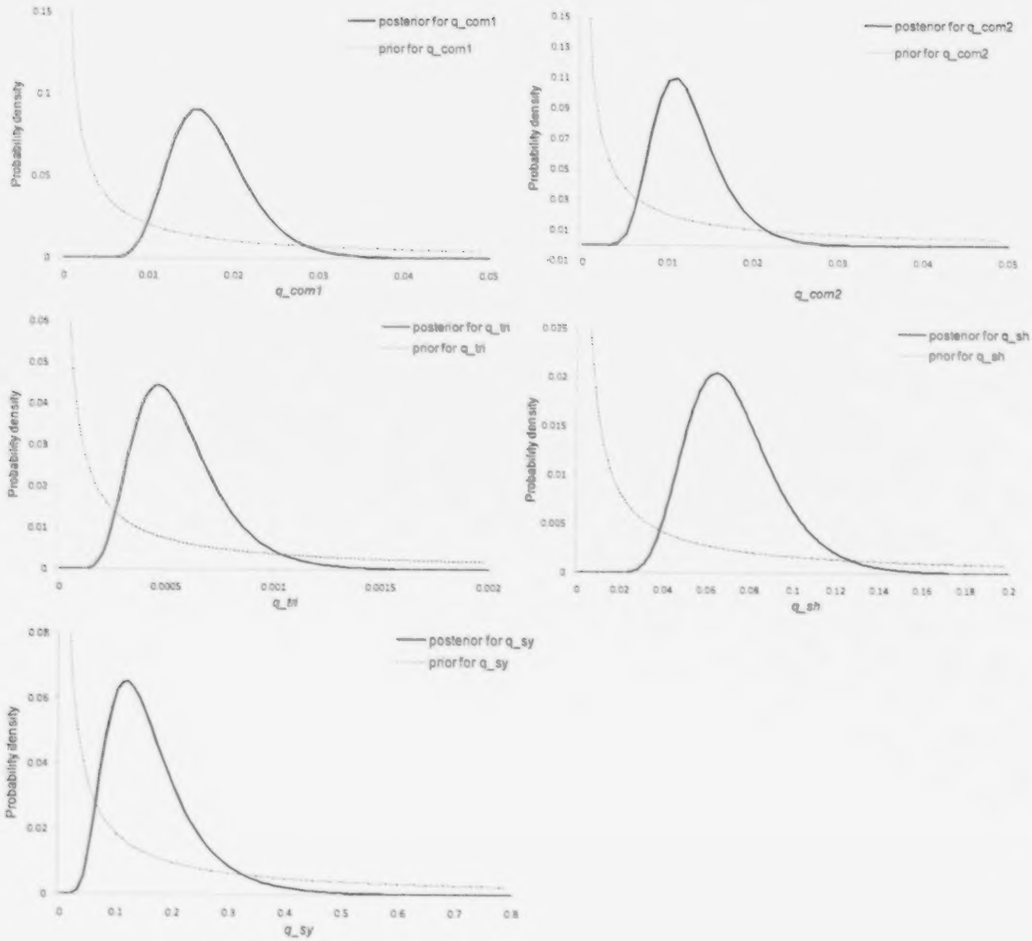
Appendix Figure 6: Marginal prior and posterior for r in the reference case. The posterior distribution has been approximated by a normal density function using the posterior mean and SD from MCMC sampling.



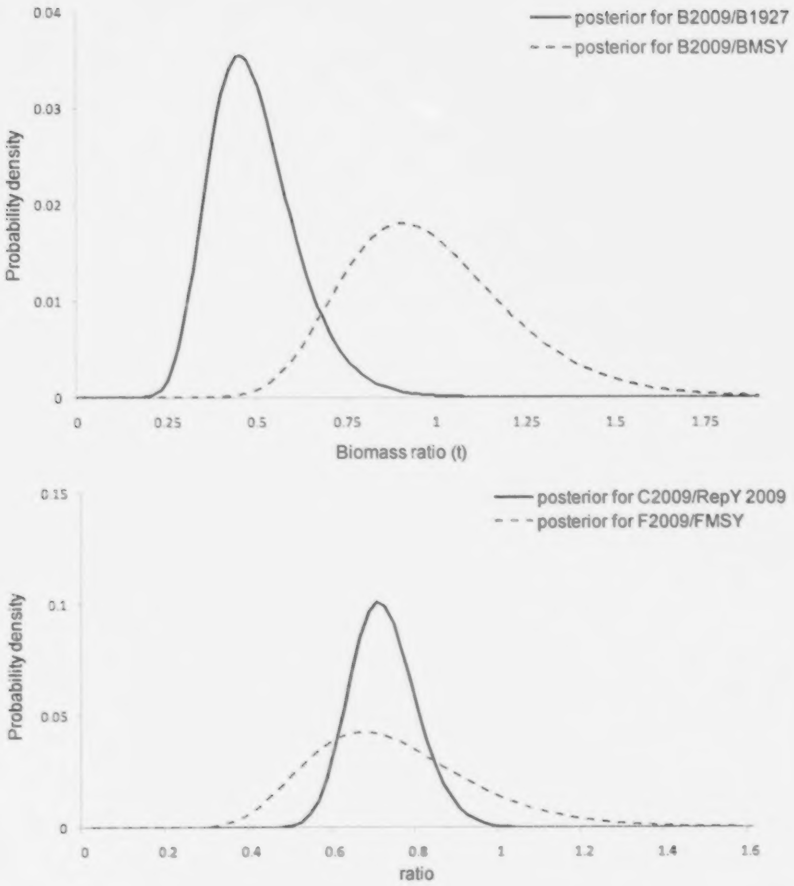
Appendix Figure 7: Marginal prior and posterior for K and marginal posterior for B_{MSY} and B_{2008}. The posterior distributions have been approximated by lognormal density functions using the posterior medians and SDs from MCMC sampling.



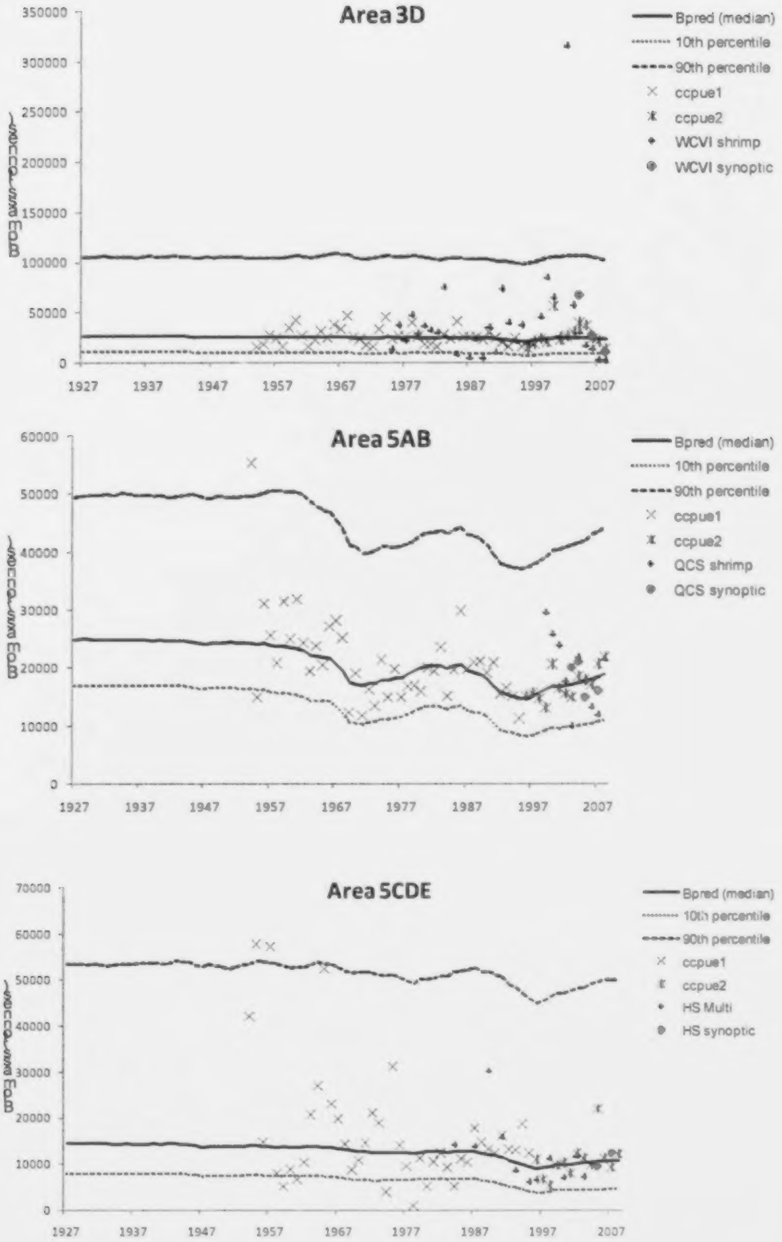
Appendix Figure 8: Marginal posteriors for $\mathrm{RepY}_{\mathrm{MSY}}$ and MSY. The posterior distributions have been approximated by normal density functions using the posterior means and SDs from MCMC sampling.



Appendix Figure 9: Marginal posteriors for the constants of proportionality for the abundance indices. The posterior distributions have been approximated by lognormal density functions using the posterior medians and SDs from MCMC sampling.



Appendix Figure 10: Marginal posteriors distributions approximated by lognormal density functions using the posterior medians and SDs from MCMC sampling.



Appendix Figure 11: Posterior median and 80% probability interval for stock biomass (in tons), and the observed stock trend indices divided by their posterior median value for the catchability coefficient for years 1927 to 2009 for area 3D, 5AB and 5CDE.

Appendix A: WinBUGS code for the stock assessment model in area 3C.

```
model
{

# Priors

# Priors for r and K
mu_r <- 0.249
sd_r <- 0.087
tau_r <- 1/(sd_r*sd_r)
r ~ dnorm(mu_r,tau_r)I(0.01,)

mean_lk <- 9.8
sd_lk <- 1.3
tau_lk <- 1/(sd_lk*sd_lk)
lk ~ dnorm(mean_lk, tau_lk)I(0.01,)
k<- exp(lk)

# tech parameter
tech <- 0.03

# Proportionnality parameters for the 5 abundance indices
lq_com1 ~ dunif(-20, 200)
q_com1 <-exp(lq_com1)

lq_com2 ~ dunif(-20, 200)
q_com2 <-exp(lq_com2)

lq_tri ~ dunif(-20, 200)
q_tri <-exp(lq_tri)

lq_sh ~ dunif(-20, 200)
q_sh <-exp(lq_sh)

lq_sy ~ dunif(-20, 200)
q_sy <-exp(lq_sy)

# Process error variance
s_p <- 0.05
tau_p <- 1/(s_p*s_p)

# Variance for the 5 abundance indices
s_o_com1 <- 0.35
tau_o_com1 <- 1/(s_o_com1*s_o_com1)

s_o_com2 <- 0.35
tau_o_com2 <- 1/(s_o_com2*s_o_com2)

s_o_tri <- 0.65
tau_o_tri <- 1/(s_o_tri*s_o_tri)

s_o_sh <- 0.6
tau_o_sh <- 1/(s_o_sh*s_o_sh)

s_o_sy <- 0.65
tau_o_sy <- 1/(s_o_sy*s_o_sy)
```

 # Management related parameters

```
MSY <- r*k/4
BMSY <- k/2
bmsy1<-0.4*BMSY
bmsy2<-0.8*BMSY
hMSY <- r/2
RatioCat <- cat[83]/MSY
RatioB <- b[83]/b[1]
```

Process equation (SSM)

```
p[1] ~ dlnorm(lpo, tau_p)I(0.001,2)
lpo <- log(1)
b[1] <- k*p[1]

for (i in 1:83)
{

        lnpvalp[i+1]<-log(pvalp[i+1])
        p[i+1]~dlnorm(lnpvalp[i+1], tau_p)I(0.001,2)
        pvald[i+1]<-p[i]+surpp[i]-cat[i]/k      # evaluate the deterministic pred of relative stock size

        surpp[i]<-p[i]*r*(1-p[i])
        pvalp[i+1]<-max(pvald[i+1],0.01)   #this prevents stock bio from dropping below 1% of K

        probp[i+1]<-step(pvalp[i+1]-0.01)      # predicted p > 0 for each year
        pbernp[i+1]<-abs(probp[i+1]-0.0000001)        # probability p = 1 for each year
        dummyp[i+1]~dbern(pbernp[i+1])      # dummy p = 1 for each year

        repyt[i]<-surpp[i]*k
        b[i+1]<-p[i+1]*k

        repy[i]<-max(0.0001,repyt[i])
        cattorepy[i]<-cat[i]/repy[i]
        pcollapse[i]<-step(0.05-p[i])
        relativebbmsy[i]<-b[i]/BMSY
        harv[i]<-cat[i]/b[i]
        relativeharvmsy[i]<-harv[i]/hMSY

}
```

Projections

```
for (i in 84:finy)
{

        lnpvalp[i+1]<-log(pvalp[i+1])
        p[i+1]~dlnorm(lnpvalp[i+1], tau_p)
        pvald[i+1]<-p[i]+surpp[i]-tac[i]/k

        surpp[i]<-p[i]*r*(1-p[i])
        pvalp[i+1]<-max(pvald[i+1],0.01)

        repyt[i]<-surpp[i]*k
        b[i+1]<-p[i+1]*k

        repy[i]<-max(0.0001,repyt[i])
        cattorepy[i]<-tac[i]/repy[i]
        pcollapse[i]<-step(0.05-p[i])
        relativebbmsy[i]<-b[i]/BMSY
```

```
        harv[i]<-tac[i]/b[i]
        relativeharvmsy[i]<-harv[i]/hMSY

        pBsupbmsy1[i]<-step(b[i]-bmsy1) # proba that B > 0.4*BMSY
        pBsupbmsy2[i]<-step(b[i]-bmsy2) # proba that B > 0.8*BMSY
        pBsupBmsy[i]<-step(b[i]-BMSY) # proba that B > BMSY
        pBfinsupBcur[i]<-step(b[i]-b[83]) # proba that Bfiny > B2009
        pFcursupFfin[i]<-step(harv[83]-harv[i]) # proba that Ffiny < Fcur

}
```

Observation equations

```
# i = 1 <=> 1927 # i = 82 <=> 2008

for (i in 54:82)
{

        LogImtri[i] <- log(b[i]*q_tri)
        Itri[i] ~ dlnorm(LogImtri[i],tau_o_tri)

}

for (i in 49:82)
{

        LogImsh[i] <- log(b[i]*q_sh)
        Ish[i] ~ dlnorm(LogImsh[i],tau_o_sh)

}

for (i in 78:82)
{

        LogImsy[i] <- log(b[i]*q_sy)
        Isy[i] ~ dlnorm(LogImsy[i],tau_o_sy)

}

learning[28] <- 1

for (i in 29:69)
{

        learning[i] <- learning[i-1]*(1+tech)

        LogImcom1[i] <- log(b[i]*q_com1*learning[i])
        Icom1[i] ~ dlnorm(LogImcom1[i],tau_o_com1)

}

for (i in 70:82)
{

        learning[i] <- learning[i-1]*(1+tech)

        LogImcom2[i] <- log(b[i]*q_com2*learning[i])
        Icom2[i] ~ dlnorm(LogImcom2[i],tau_o_com2)

}

}
```

Data area 3C

catches in tons

```
list(
finy=123,
dummyp=c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,
1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1),

lcom1=c(NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
NA,122.9,237.5,310.1,298.1,355.8,311.9,213.7,311.8,227.4,345.3,419.1,367.9,307.7,422.6,602.7,288.8,281
.7,358.1,286.3,350.7,303.5,370.0,247.7,288.3,225.9,260.3,282.6,261.8,411.8,371.9,445.1,531.5,379.6,206.
2,208.3,315.7,278.2,302.2,354.1,671.0,237.2,256.9,147.8,239.1,482.8,254.9,270.3,312.0,284.0,443.1,672.7
,513.9,628.6,344.1,401.7),

ltri=c(NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,3125,NA,
NA,8956,NA,NA,NA,NA,NA,8436,NA,NA,2821,NA,NA,3335,NA,NA,3207,NA,NA,1326,NA,NA,NA,NA,NA,N
A,NA),

lsh=c(NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,1371.5,1519.2,408.6,534,95
0.7,962.2,934.2,778.4,2311.5,NA,562.6,NA,301.2,330.6,401.1,304.8,429.1,253,193.1,262.2,251.8,213.2,21
6.1,333.1,190,494,281.9,992.5,655.9,303,2476.9,2069.6,431.1,1268.2),

lsy=c(NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,N
A,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,1739.9,NA,1922.1,NA,712.
1),

cat=c(244.64,258.71,186.59,174.25,102.14,89.80,89.96,126.27,244.59,229.47,36.42,236.75,154.91,555.40,
231.69,269.39,357.13,289.18,287.96,384.04,110.77,243.82,378.34,529.37,729.85,453.20,356.13,1048.84,1
412.29,1301.86,1362.16,1199.53,1915.64,2090.59,2113.87,1123.97,831.15,1289.94,2017.62,2235.41,2048
.31,1871.33,1263.16,1026.62,1225.07,910.43,1073.21,1301.78,1877.99,1467.73,1117.97,569.09,789.96,84
2.98,851.02,1737.01,1147.43,1868.73,3618.23,1102.67,742.46,690.12,993.22,1418.01,1448.89,1125.50,16
46.87,881.47,1009.26,898.58,652.52,688.64,411.66,633.21,563.66,555.19,677.06,782.30,927.67,875.99,71
8.12,824.35,824.35),

tac=c(NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA
,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,N
A,NA,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,
950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950,950)

)
```

Inits

```
list(lk=9.9,lq_com1=-4, lq_com2=-4.2, lq_tri=-0.45, lq_sh=-2.45, lq_sy=-1.6,r=0.25)
```